Energy Management for Islanded Microgrid with Energy Storage Systems

By

Xueying Wang

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Author's Declaration

I declare that this thesis is my own account of my research and contains as its main content work which has not previously been submitted for a degree at any tertiary education institution.

Abstract

Microgrid is a new form of electrical network interconnected with renewable energy resources mainly used for remote areas. A microgrid has two operational modes, grid-connected and isolated modes. In isolated mode operation, the microgrid needs to overcome the intermittent power generated by renewable energy resources (PV or wind turbines) as the amount of generation is largely affected by weather condition. In order to optimise the power dispatch and maintain power-quality for an islanded microgrid, an energy management system for a low-voltage islanded microgrid with an energy storage system (battery in this thesis) is presented.

The main objective of this energy management system is to optimise power dispatch and to make effective use of power generated by renewable resources (solar power in this paper) for an islanded microgrid to achieve the purpose of installing an environmental friendly power grid. The proposed energy management system is divided into two parts. Firstly, the system determines the battery charging/discharging state and the backup DG operating time based on the power generated by PV, base DG and load demand in each time step. From the decision-making process, the battery power, battery state of charge and the backup DG operating time is available for the next stage of the energy management system.

Secondly, the modified Gauss-Seidel load flow iteration process is run in MATLAB for computing the bus voltage and transmission line power losses in each time step. The Gauss-Seidel load flow analysis is a typical calculation strategy for evaluating the operation of power flow in an electrical network. In order to verify the effectiveness of the proposed energy management system, four case studies are provided in this report under different power profiles and load profiles. The energy management system is used not only for optimizing power dispatch for an isolated microgrid with renewable energy resources and an energy storage

system, but also for sizing battery and diesel generators before the installation of the microgrid with reasonable prediction of load demand and renewable power generation.

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Chapter 1: Introduction

Along with the population growth in the world, the demand of power generation is increasing, causing a series of unavoidable problems to the traditional electrical network, especially the demand of reliable and sustainable energy resources[1]. Meanwhile, people live in different areas increase the requirement of more power supply for industrial and daily use, if the current electrical network do not update on time, problems such as low power-quality and sudden power off even power grid failure, eventually leading to economic losses. On the other hand, the traditional power grid mainly depends on conventional synchronous diesel generators using fossil fuel as the power source which caused the energy crisis and pollution problems. Meanwhile, the research of renewable energy resources such as photovoltaic system and wind turbines has reached a new level with reliable technology for producing high-quality power.

It is difficult to keep high and reliable power quality for remote areas with a traditional interconnected power grid. The construction of the transmission line is costly, and the transmission line power losses increase as the length of the transmission line increases. On the other hand, some remote areas may have sufficient renewable energy sources and available space which is suitable for a small-scale stand-alone power grid locally. In order to gain a reliable, stable, and high-efficiency electrical network system for such areas, a modern form of the traditional power grid with more secure and dependable electrical services has attracted more attention in recent decades. Microgrid systems are new form of the electrical network system, combining the advantages of the conventional power grid and stand-alone power grid as well as maximizing the use of renewable energy resources. A Microgrid system, as part of the modern power grid model, is a small-scale distributed network built mainly for remote areas with sufficient renewable power resources. Under this condition, renewable energy resources such as photovoltaic and wind sources play an important role in the power generation system as well as decreasing the emission of greenhouse gas, however, the intermittent power generation leads to a difficulty in power dispatching, causing imbalances in the system and system failure. This could damage the grid and cause serious economic losses. In order to solve this problem, renewable energy resources such as photovoltaic panels and wind turbines are usually followed by an energy storage system for stabilizing power generation and system frequency.

The microgrid is a distributed system connected to the utility grid via Point of Common Coupling (PCC) with distributed energy resources, typically they consist of renewable energy resources as main power generation devices, distributed generators as assistant resource, backup resources, energy storage system (ESS) stores excess energy and also used as a power source. Figure 1 shows the structure of a typical microgrid system[2].

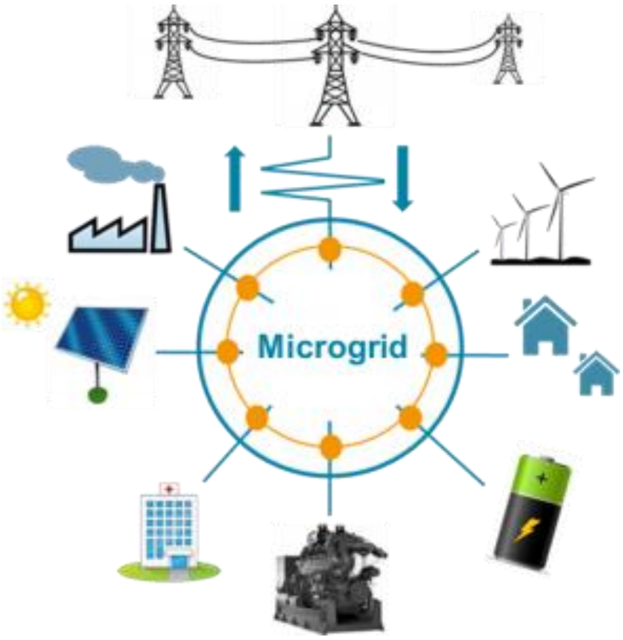

Figure 1 Microgrid system structure [2]

The U.S. Department of Energy Microgrid Exchange Group defines a microgrid as a “group of interconnected loads and distributed energy resources (DERs) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid”[3]. As a microgrid contains a power generation system, self-control and self-protection system, it can connect to the utility grid which is grid-connected mode or disconnected from the main grid which is isolated mode. In grid-connected mode operation, the microgrid is treated as a sub-system of the utility grid, where the utility grid helps to stabilise the frequency and power generation. In the isolated mode, the system is a self-sufficient power grid with all the load supplied by the power sources in the system.

As a new form of the power grid, a microgrid system is a small-scale electrical network with DERs. The difference between a conventional power grid and a microgrid, according to [4], a microgrid has the characteristic of intelligent power dispatch compared with the conventional power grid. A microgrid system is composed of various power generation devices including conventional DGs, single or multiple renewable energy resources and an energy storage system. If accidents happen, the DG will be disconnected from the microgrid, then the microgrid can offer "black start", increasing power supply reliability. The power dispatched from DERs, renewable sources and energy storage system, as well as to meet the load demand of un-controllable loads is the main challenging problems of the isolated microgrid. This problem leads to the research of microgrid controlling and management strategies.

In recent years, as the requirement of high power-quality increases, the management of the microgrid system attracts more attention. The management and control strategies are key issues for keeping the microgrid system operating successfully and effectively, especially in isolated mode. For a grid-connected microgrid, it is treated as the sub-system of the utility grid. When the occasional power imbalances take place inside the microgrid network, it can be overcome by sub-station, and the excess power generated by renewable resources and DGs in the microgrid can be traded with the main grid. In islanded operation mode, the grid is disconnected from the utility grid. The microgrid should have the capability of self-protection and self-sufficiency. The power dispatch of intermittent power generated by renewable energy resources and an uncertain load demand at each time step. Solving this problem, result in the energy management system is becoming a hot research area in recent years. Microgrid energy management system (EMS) is considered to optimise the power quality in islanded mode. To be more specific, the energy management system optimises the power flow, balancing the power generation and load demand. Furthermore, the energy management system is responsible for effectively using renewable energy resources when dispatching power generated by various power sources at the same time. In single isolated microgrid control and management, the EMS has the highest level by coordinating each energy resources in a specific time horizon, balancing the power flow within the system to guarantee the reliability and high-efficiency.

The challenges of an energy management system come from many aspects. Firstly, for the purpose of constructing an environmental friendly electrical network, the sequence of power dispatching should be taken into consideration because the microgrid is composed of various power generation devices. Secondly, when accidents happen during the islanded mode operation, the energy management system should react quickly to maintain the power generation and avoid entire power failure and then causing economic losses. Thirdly, as the demand for "green" energy production increases significantly over the years[5], the energy management system should effectively make use of power generated by renewable power sources effectively. Lastly, the energy management system is also responsible for optimizing the operational cost for a system.

This study presents a microgrid energy management system for a low-voltage residential microgrid test-system in an isolated mode. The microgrid can be divided into two parts, the power generation side and the power consumption side respectively. In order to supervise and dispatch intermittent power generated by renewable energy resources, a real-time energy management system is provided in this thesis. In each time interval t, the EMS exchanges signals with the power generation devices and the load in the islanded microgrid, sending signals to the energy storage system and backup power resources. The purpose of the storage system is to maintain constant power generation in the microgrid by storing excess power, and the backup power source is operated in case of sudden breakdown and extremely high load demand in a certain time step. The Gauss-Seidel load flow iteration process is for evaluating the performance of the system.

The purpose of the energy management system is to get a reasonable power dispatch based on the given power generation and consumption profile, to optimise power dispatch for an islanded microgrid by effectively making use of intermittent solar power generation. On the other hand, the energy management system provides a possible power flow based on the solar power and load demand prediction which is necessary before the installation of the microgrid in order to size the battery and diesel generators.

The remaining of the thesis is organised as follows: Chapter 2 is a review of the energy management system from previous papers. Chapter 3 presents the structure of the energy management system as well as the method of implementing the system. A simplified model of the low voltage islanded microgrid is also provided in Chapter 3 for a further feasibility study. Chapter 4 presents four case studies based on different given power profile and load profile and discusses the results of these cases. At last, the contribution of the main work and the forward of future work is highlighted in Chapter 5.

Chapter 2: Literature Review

A microgrid system is a new model of distributed energy resources in an interconnected power grid. A typical microgrid system includes distributed energy resources such as a conventional generator, backup generator, energy storage system and renewable energy resources. According to "Integration of Distributed Energy Resources in the Operation of Energy Management System"[6], distributed energy resources can be characterized by:

- A large number of generating units of small to medium capacities
- Little or no telemetry (although this situation is gradually evolving)
- Power injected at many different points in the grid
- Power injected at low voltage, distribution levels.

The microgrid is a two operational modes electrical network. Compared with the traditional power grid, the microgrid is smarter in power dispatching[4] with multiple power generation devices. Typically, a microgrid system is installed with some large or small-scale intermittent resources, referred as renewable energy resources[4]. In the microgrid system, the energy management system is used to maintain the constant power generation. The performance of the isolated microgrid management and control depends on the power dispatch of DERs. Since isolated microgrid disconnected from the utility grid, the power generation rely completely on DERs. The ability of monitoring and controlling the power dispatch is the main challenge of controlling and managing a microgrid.

In most of the literature, the control of a microgrid is a hierarchical process, including primary control (droop control or local control), secondary control and tertiary control. As the first layer of control, droop control is used to stabilise the system frequency in the islanded mode. Since the output of each inverter has different frequencies, droop control in the islanded-mode microgrid is to maintain the system in steady-state[7].

In “Coordinate Control of Distributed Generation and Power Electronics Loads in Microgrids”[8], a load frequency trimming control is proposed to participate in a supply-demand balance service to maintain and enhance the system reliability, only using control variables of the converter itself that can be measured locally. Through the frequency trimming control strategy, supply-demand balance can be realised automatically, and the microgrid can avoid malfunction. The proposed load frequency trimming control principle provides instantaneous reserves when the microgrid is overloaded. Under this condition, power electronics load reduce its real power consumption or release more reactive power. In order to implement this control strategy, the microgrid frequency and voltage should be sensed. The power electronics load only participate the supply-demand balance service when the microgrid frequency equals its allowable minimum frequency or the voltage equals its allowable minimum voltage, and the DG units reach its largest power generation capacities. The proposed microgrid control strategy is based on the primary control (droop control) by providing power electronics load in case of emergency. However, the energy management system controls the power dispatch from the power distribution side of the microgrid.

The energy management system is the secondary control of the microgrid, aiming for optimizing power quality and power dispatch. The optimal control and management of the microgrid system is an important hot research direction in recent years as the demand of a higher power-quality, reliable and high-efficiency microgrid system. The control and management of microgrid is a hierarchical process, and microgrid management system is also known as secondary control. The main function of the MG energy management system is optimizing the power dispatching, unit commitment, and operation cost. The EMS receives load information from the primary control, then the optimal schedules of dispatching DERs and energy import/export are obtained by solving optimisation problems. Various techniques, such as dynamic programming, particle swarm algorithms, mixed-integer linear/non-linear programming can be utilized to solve the energy scheduling problem [9].

In “Optimal Power Flow for a System of Microgrid with controllable loads and battery storage”[10], a particle swarm optimisation (PSO) strategy is provided and implemented in a wind farm microgrid system. The PSO is used to speed up the convergence and to achieve better minima. According to the microgrid system discussed in this paper, the loads are controllable, and the wind and solar powers are constant. The controllable loads are assumed to be curtailable for up to one hour after which they must be increased to 110% of their initial value for the next two hours to consider the start-up power and thermal inertia of the loads. The optimal power flow (OPF) is a way to optimise the steady state performance of the power system with respect to a given objective function while satisfying a set of equality and inequality constraints[10]. OPF, along with a PSO algorithm decreases the operational cost by 14.2% and provide over 10 MW of power according to the system in the paper. Furthermore, in paper “A Real-time optimal energy dispatch for microgrid including battery energy storage”[11], a real-time optimal energy dispatch is proposed based on the particle swarm optimisation algorithm as well. The proposed energy dispatch reduces the energy loss and avoids some predictive error accumulation compared with conventional energy dispatch. The proposed strategy in literature [11] is based on the real-time price, the forecasted DG, load and the current state of charge and constraints of the microgrid. The microgrid purchases or sells energy according to the actual microgrid state.

There are two main approaches which can be identified in the secondary control: centralized and decentralized. The differences between these two approaches is that: the decentralized approach aims to achieve economical operation of a microgrid while providing the highest possible autonomy to the different DERs and loads. The centralized EMS approaches have focused on the mathematical model of the microgrid operation and components with emphasis on Mixed-Integer Linear Programming (MILP) formulations. In the literature [12], a centralized EMS mathematical model is provided. The main function of this mathematical programming is the dispatch of available resources for a three-phase microgrid system. The model includes constraints associated with the operational limits of the generating units, power flow/power balance, energy balance of the energy storage systems, system operator settings and spinning reserve. The proposed model is a multi-stage programming system based on rectangular coordinates for phasor representation and series elements are represented using three-phase ABCD parameters matrices. The EMS decomposed difficult mixed-integer non-linear problems into a MILP and a nonlinear programming problem. To be more specific, power flow is replaced by a simple linear, real power, demand-supply balance equation in literature[12]. On the other hand, the EMS takes the unit commitment decision variables as fixed parameters. This EMS model simplified the complex nonlinear problems to a linear problem which is typically much easier and faster to solve. There is one point to be noticed in this literature, where the forecasting system accuracy may have an impact on the performance of the EMS on the provided optimal solutions given. In order to gain better dispatchable solutions from EMS, the accuracy of the forecasting system, as well as the voltage and frequency set points set by the droop controller not necessarily be optimised. The system described in [12], provides a mathematical model and control architecture of an autonomous EMS for isolated microgrid which concentrates on a three-phase system.

The centralized model presented in [12] concentrated on the power dispatch process, as the uncertainty of renewable energy resources and sudden fluctuation in an isolated microgrid system, demonstrates a robust optimised model needs to be taken into consideration. By comparing the reliability of centralized and distributed EMS [9], it is shown that the distributed

EMS significantly improved the reliability indices by more than 50%. However, centralized EMS framework raises almost five times faster than distributed EMS framework. The same reliability index can be achieved by the distributed solution with less reliable controllers.

In literature “A Mixed Integer Programming Model for Intra-day Microgrid Scheduling”[13], a Mixed-Integer Linear Programming model is used for a microgrid energy management system by coordinating real and reactive power output constraints of DGs and branch capacity constraints. An intra-day scheduling model is built in [13], using the predictive maximal power output of renewable energy and load demand for determined time intervals. This paper focuses on the prediction system. Instead of using short-term prediction and day-ahead prediction technology, this paper provided an intra-day scheduling based on super short-term prediction technology in the hour-minute level. This scheduling of the first interval is set as the initial value in the next scheduling cycle. After finishing an intra-day scheduling cycle, the time window moves forward by one-time scale. The advantage of this rolling optimisation strategy can effectively reduce the errors caused by short-term prediction in day-ahead scheduling.

However, the MILP formulations in literature [13] presents little on a distribution system. More importantly, for an isolated microgrid system, a decision-making framework is necessary as the system coordinate to find the optimal operating point within the independent system. An integrated Energy Management system for islanded microgrid is provided in [14], focusing on the dispatch problems and the impact of model predictive control implementation and forecast errors. The mathematical model provided in the literature considers the dispatching and scheduling of distributed energy resources and the network flow constraints and along with operational constraints associated with DERs. As demand side management, customers are a part of the management system by shaving or shifting load during peak-load hours or system contingencies, which increase the reliability of the system. The model presented in the paper used a Model Predictive Control (MPC) approach for tackling deviations in the forecast of renewables and electricity demand. On the other hand, the proposed system is a mixed integer non-linear programming model using a current MINLP solver based on a medium-voltage system with a PV system and wind power system. By comparing with the decoupled energy management system based on realistic and complex isolated microgrid system, the results showed the benefit of the integrated system, it consisted of less operation cost and load curtailment by optimal use of energy storage system and other generation resources.

Besides mixed integer linear or non-linear programming for isolated microgrids, such as in "Energy Management of Isolated Microgrids Using Mixed-Integer Second-Order Cone Programming"[15] provides a mixed-integer second-order cone model for microgrid energy management. The mathematical model is convex for radial topologies, guaranteeing convergence and global optimally[15]. The model contains both active and reactive power balances, dispatchable DG and ESS unit commitment, fuel availability and system operational constraints. Load shedding is controlled by a continuous demand-side management (DSM) which is included in the model in order to minimize the amount of unserved energy. The test system provided in the paper considered two scenario-----5-hour and 24-hour. Both cases showed that if the fuel limitation is taken into consideration, the unserved energy and operational cost increases, due to more curtailed load. In other words, the results showed that not addressing fuel limitation into the model might lead to fewer conservation results and eventually to bigger energy management errors in paper [15].

However, the use of a complex mathematical model either linear or non-linear is decreasing over recent years. Centralized EMS transfers its concentration to the distribution system. The traditional centralized model can incur a significant cost for new transmission lines, which causes concern regarding system stability, and presents challenges for system flexibility [16].

As a result, logical alternative solutions to solve these challenges have been proposed in recent years. These modern models are normally smaller in capacity, adaptable in structure, and installed close to customer load demand. Diesel generators and renewable energy resources (PVs and wind turbines) provide an alternative means to derive electrical power without placing additional pressure on fossil fuel-based supplies. Emerging and existing DER technologies are primarily DC generation sources, rectified high-frequency AC sources, some conventional generation sources and storage systems. For example, in [16], an agent-based microgrid energy management system is discussed. A multi-agent system is a collection of autonomous computational entities. Each agent exchanges information and cooperates with each other. The challenge for a multi-agent system is that it needs to be self-cooperated and applying for the isolated microgrid. In literature [17], a Multi-Agent system is used for implementation of the decentralized energy management system for the microgrid instead of a complex mathematical model. This control strategy is based on real-time measurements, including several autonomous decision-making entities such as a PV agent and DG agents. A multi-agent framework reacts to real-time changes in the microgrid in each time interval. In literature "Intelligent Control System for Microgrids Using Multiagent System"[17], the multi-agent strategy consists of several autonomous decision-making entities such as a PV agent, a PCC agent and a bus agent. Each agent represents a major autonomous component of the microgrid. There is no central control agent in this system, and agents communicate with each other. The proposed MAS was implemented in an open source multiagent development framework in the java language which simplifies the implementation of the agent systems.

In the microgrid energy management system, algorithm type model are also used for the optimal power dispatch of generation units ([18] and [19]). An energy management system for a medium-voltage microgrid is provided in [18] based on the Dongao Island Renewable Energy Microgrid Demonstration Project in China. The main function of this system is to meet the requirement for the microgrid steady control when the system's voltage and frequency are stable in the isolated microgrid. It also provides enough system reserve capacity for the microgrid so that the system can respond to equipment failures and high volatility. The algorithm provided in this paper compares the load rate at time t (one time interval) with the maximum and minimum limit. After the comparison, the system balances the power flow inside the microgrid by controlling the operation of wind turbines and the diesel generator, as well as controlling the state of charge of the battery bank. The energy management system proved to be effective. In "Energy Management System for an Isolated Microgrid with Photovoltaic Generation"[19], a weighted algorithm is presented by comparing the power generation and load demand in an isolated microgrid system. It is argued that a faster approach is gained via the weighted algorithm than a MILP-based model. However, the weighted energy management algorithm provided in this paper relies fully on photovoltaic energy. In other words, there is no stable power generation during the daytime. Under this condition, if the solar power suddenly breaks down, the whole system would be a failure, leading to serious financial loss.

An energy management system of a microgrid system have many different functions. As mentioned in "Energy Management System for Microgrid With Power Quality Improvement" [20], a unified power quality controller (UPQC) is used to mitigate voltage and current related problems simultaneously. The proposed system is able to compensate active power transfer to load, power generated by power sources, voltage barrier and help to improve power quality. UPQC is the combination of series and shunt active power filters for mitigating power quality issues. Two voltage source inverters are used to function as series and shunt active power filters. The test results are obtained for various conditions of power generation and load distribution. UPQC is connected across a non-controllable load as the system priority is continuously supplying a critical load. The result showed that UPQC can mitigate the supply and demand side disturbance like voltage sag. An energy management controller is developed to control the gate signal of switches that are connected at the source and load side and the UPQC is provided to improve the power quality. The EMS along with UPQC manage the microgrid system better than using each system individually. In paper “Real-Time Energy Storage Management for Renewable Integration in Microgrid: An Off-Line Optimization Approach”[21], a new off-line optimisation approach for real-time energy management system is provided. The main approach in this paper is to model the renewable energy offset by the load over time to minimize the total energy cost.

As the highest level of microgrid control, the function of the EMS is variable, depending on the requirement of customers. The EMS system provided in the next section, is based on the Gauss-Seidel load flow analysis, which involve programming an algorithm for the dispatchable power from diesel generators, renewable energy sources (PVs in this system) and a battery unit. The main function of this EMS is to keep the power balance along with un-controllable loads. To meet the variable load demand, as well as minimizing the usage of diesel generators, and maximizing the usage of PV and battery power generation.

Chapter 3: Methodology and System Description

3.1 Mathematical model

In this section, a microgrid energy management system is proposed. In islanded-mode, the microgrid is disconnected from the utility grid via the PCC. As a result, the islanded microgrid should be capable of self-sufficiency and self-protection. Without the connection to the utility grid, the DG in an islanded microgrid needs to compensate for the power imbalance and voltage imbalance. On the other hand, the power generated by renewable power resources and the battery bank discharging is intermittent compared with traditional distributed energy resources. The main function of the EMS is to optimise the power dispatch within the islanded microgrid as well as leaving reverse capacity in case of a sudden breakdown and extremely high load consumption in the microgrid operation. The EMS also predicts the power dispatch condition before the installation of the microgrid based on the power generation/consumption in the islanded mode. In the control and management of microgrid, energy management is the secondary control, the system frequency and voltage output is in steady-state. The energy management system extracts information from the primary control layer, then dispatches the power generated by PV and diesel generator. The main concept of this process is to compare the relationship between the uncontrollable load demand and the intermittent power generation from solar power at each time step. On the other hand, the microgrid needs to satisfy the load demand and the battery is used for reverse capacity for the microgrid. Furthermore, it is necessary to consider that when the load demand is extremely high, the EMS should react to this situation in a short time, avoiding the failure of the power grid.

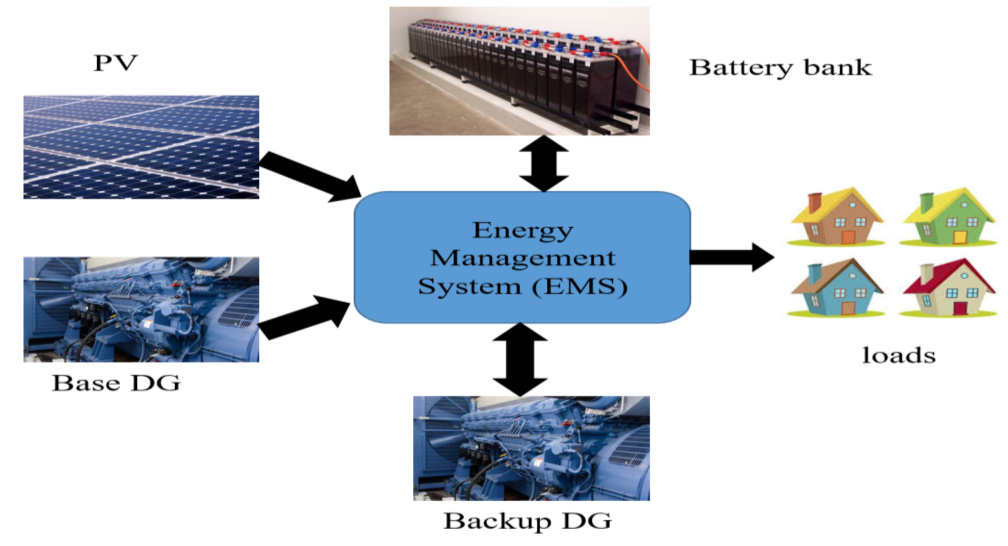

Figure 2 EMS concept map

Figure 2 shows the basic structure of the microgrid energy management system. EMS collects power generation "information" from the base DG and photovoltaics system, and power consumption "information" from the customer-side. Then, the system compares the relationship between the power generation and consumption and decide the battery input power according to the battery state of charge and the backup DG operation state to complete the power dispatch. If the backup DG should operate in a certain time step, the EMS will send a "signal" to the backup DG. The EMS is a "Data Centre", collecting and processing data from various devices in the microgrid, and deciding the power dispatch result for the microgrid.

In order to achieve an ideal sequence of successfully power sources dispatch, the proposed EMS is divided into two parts, the decision-making part, and decision-executing part. In this project, the proposed EMS is applied for an isolated low voltage microgrid with an energy storage system (battery bank).

I. Decision-making process: Firstly, the decision-making process corresponds to logical decision analysis. The main function of this process is to compare the relationship between power generation and load demand in each time interval t. The decision-making process transfers the comparison result to the next process---decision-executing process. In this system, one day is used as a time horizon and one hour as one time interval. In the islanded microgrid system with renewable energy resources and energy storage system, the power balance within the system should satisfy the equation below:

$$P_{DG}(t) + P_{PV}(\mathrm{t}) = P_{load}(t) + P_{loss} \quad (1)$$

The power generation should equal to the power consumption in a typical and perfect microgrid system. In most cases, equation (1) cannot be satisfied because of the intermittent power generation from the photovoltaic system (P_{PV}) and uncontrollable load demand (P_{load}), leading to the inequalities shown in equation (2) and (3) below:

$$P_{DG}(t) + P_{PV}(t) > P_{load}(t) + P_{loss} \quad (2)$$

$$P_{DG}(t) + P_{PV}(t) < P_{load}(t) + P_{loss} \quad (3)$$

In order to keep the power balance in the system, the EMS compares the relationship between P_{DG}, P_{PV} and P_{load}, then according to equation (1), (2) and (3) and the battery state of charge, decides where the excess power should go. According to equation (4),

$$[P_{DG}(t) + P_{PV}(t)] - (P_{load} + P_{loss}) = P_{excess} \quad (4)$$

According to battery charge of discharge condition, the excess power (P_{excess}) is dissipated to a dump load or charge the battery. The flow chart of the decision-making process is shown in Figure 3.

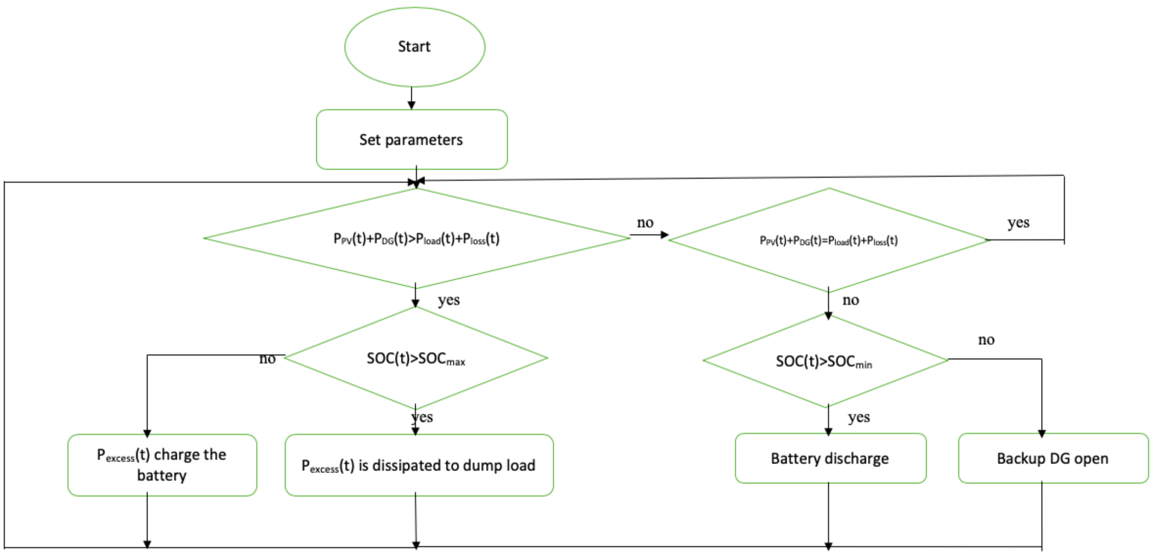

Figure 3 Flowchart of EMS

The main parameters in this flowchart is shown in ..

NOMENCLATURE	VARIABLE
P_{PV}	power generated by PV
P_{DG}	power generated by base diesel generator
P_{LOAD}	load power demand
P_{LOSS}	power loss
SOC	Battery state of charge
SOC_{MAX}	Maximum state of charge (90% typically)
SOC_{MIN}	Minimum state of charge (20% typically)
P_{EXCESS}	Excess power within system

Table 1 Parameters illustration

The flowchart in Figure 3 shows the EMS decision-making process. In this system, it is assumed that the frequency is stabilised by the primary control layer before the data is transferred to energy management system. Then, the EMS compare the power generated by PV and base diesel generator with load demand in every time interval.

According to equations (1), (2) and (3), the decision-making process is divided into three parts. In the first case, corresponding to equation (1), if the power generated by the PV and the DG is equal to the power consumption, the system will move to the next time step until the power generation is not equal to the consumption. In the second case, corresponding to equation (2), if in any time step, the power generation is greater than the power consumption, and, if the battery state of charge (SOC) is lower than the allowable maximum state of charge (SOC_{max}), the excess power will be dissipated to charge the battery until next time step. Otherwise, the excess power will be dissipated to the dump load. In the third case, corresponding to equation (3), if the power generation is smaller than the power consumption. In this case, if the battery SOC is higher than the allowable minimum SOC (SOC_{min}), the battery will discharge to compensate for the excess load demand. Otherwise, the battery SOC reaches the allowable lowest SOC value, the EMS will send signals to operate the backup DG automatically to complete the power flow in this time step. This process is repeated in each time step, the energy management system collects and processes the power generation and consumption data, gives a reasonable power dispatch result.

II. Decision-executing process: The evaluating of this EMS is based on the Gauss-Seidel load flow analysis. The Gauss-Seidel is an iterative method for solving a linear system of equations. In Gauss-Seidel method, once the variable $x_1^{(k+1)}$ is computed from the first equation, its value is then used in the second equation to obtain the new $x_2^{(k+1)}$, and so on. The Gauss-Seidel equations are shown in from equation (5) to (8).

For each $k \geq 1$, generate the components $x_i^{(k)}$ of $x^{(k)}$ from $x^{(k+1)}$ by

$$x_i^{(k)} = \frac{1}{a_{ij}}[-\sum_{j=1}^{i-1}(a_{ij}x_j^{(k)} - \sum_{j=i+1}^{n}\left(a_{ij}x_j^{(k-1)}\right) + b_i] \quad (5)$$

for i= 1, 2, …, n

namely,

$$a_{11}x_1^{(k)} = -a_{12}x_2^{(k-1)} - \cdots - a_{1n}x_n^{(k-1)} + b_1 \quad (6)$$

$$a_{21}x_1^{(k)} + a_{22}x_2^{(k)} = -a_{23}x_3^{(k-1)} - \cdots - a_{2n}x_n^{(k-1)} + b_2 \quad (7)$$

$$a_{n1}x_1^{(k)} + a_{n2}x_2^{(k)} + \cdots a_{nn}x_n^{(k)} = b_n \quad (8)$$

The matrix form of the Gauss-Seidel method us as follows:

$$(\mathrm{D} - \mathrm{L})x^{(k)} = Ux^{(k-1)} + b$$

$$x^{(k)} = (D - L)^{-1}b$$

Defining $T_g = (D - L)^{-1}U$ and $C_g = (D - L)^{-1}b$, then the Gauss-Seidel method can be written as

$$x^{(k)} = T_g x^{(k-1)} + C_g \qquad \text{k=1,2,3…}$$

Applying this method for an electrical power system, in an n-bus system, the initial voltage of the i^{th} bus by $v_i^{(0)}$, i=2,…,n, which means the voltage of the i^{th} bus at the 0^{th} iteration. In the Gauss-Seidel load flow analysis, the first step in the iteration is to compute the admittance matrix for the network based on the given transmission line impedances. This is shown below:

$$Y_{bus} = \begin{bmatrix} Y_1 & -Y_{12} & -Y_{13} & \cdots & -Y_{1n} \\ -Y_{12} & Y_2 & -Y_{23} & \dots & -Y_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -Y_{1n} & -Y_{2n} & -Y_{3n} & \cdots & Y_{nn} \end{bmatrix} \quad (9)$$

Then, he real and reactive power injected at any bus is known, as it can be expanded as follows:

$$P_{i,inj} - jQ_{i,inj} = V_i * \sum_{k=1}^{n} Y_{i,k} V_k = V_i^* [Y_{i1}V_1 + Y_{i2}V_2 + \cdots + Y_{ii}V_i + \cdots + Y_{in}V_n] \quad (10)$$

This equation can then be rewritten as:

$$V_i = \frac{1}{Y_{ii}} [\frac{P_{i,inj} - jQ_{i,inj}}{V_i^*} - Y_{i1}V_1 - Y_{i2}V_2 - \cdots - Y_{in}V_n] \quad (11)$$

According to equations (9), (10) and (11), the voltage on each bus can be computed. In each time step, the energy management system model collects power generation data from the PV power generation, load demand, and battery condition (charging or discharging), the data is then processed to the iteration process to evaluate the system operation for overvoltage problems. Then, the transmission line losses can be computed from (12) in each time interval as follows.

$$P_{loss} = (\frac{V_{line}}{R_{line}})^2 * (R_{line} + j\ x\ X_{line}) \quad (12)$$

The function of the base DG in this system is to provide constant power generation as well as balancing the system power flow. It is assumed that the base DG on slack bus has a base power (1 p.u), and the base DG adapts to the total power from other power sources and load (13). As following equation shows.

$$P_{base\ DG} = P_{load} + P_{pv} + P_{battery} + P_{backup\ DG} + P_{dump\ load} + P_{line\ loss} \ (13)$$

The mathematical model is applied to the implementation of EMS in programming language, which will be discussed in the next part.

3.2 Energy management system programming

According to the mathematical descriptions provided in 3.1 section, in order to implement the energy management system with the support of related software, the mathematical model should be implemented in a program. In this project, the main programming software was

MATLAB. At first, the flowchart in Figure 3 was programmed in MATLAB with “for-loop” and “if- structures” as shown in Figure 4.

```
for t=1:24
    generation=a(1,t);
    load=b(1,t);
    if (generation>load)
      if (SOC>=0.9)
%   'dissipated to dump load'
           SOC=SOC;
      else
      SOC=SOC+(generation-load)/60;
      Pb=generation-load;
%      charge the battery
         if SOC>=1
           SOC=0.9;
%       battery full
         end
       end
 elseif (generation<load)
     if SOC>0.2
      SOC=SOC-(load-generation)/60;
       Pb=generation-load;
%      battery discharge
       if SOC<=0.2
         SOC=0.2;
%      battery cannot discharge
       end
    else
     SOC=SOC+(generation-load)/60;
%      backup DG open
      end
    else
    SOC=SOC;
% battery no generation and consumption
    end
 t
SOC
end
```

Figure 4 Decision-making process

Setting 24-hour as a time horizon and one hour as a time step, the program computes the battery bank power generation/consumption and the time of the backup DG takes part in the power flow process. Then, the battery state of charge is computed according to the amount of power generation, consumption and battery capacity.

The Gauss-Seidel load flow analysis is used for computing the voltage magnitudes on each bus. According to equation (9) to (11), the Gauss-Seidel load flow analysis is programmed into MATLAB as shown in Figure 5.

```
while (iteration<1000)
  for i=2:nbus
     sumyv=0;
    for k=1:nbus
      if i~=k
     sumyv=sumyv+ybus(i,k)*V(k);
      end
    end
  if type(i)==2
Q(i)=-imag(conj(V(i))*(sumyv+ybus(i,i)*V(i));
   if (Q(i)>Qmax(i))||(Q(i)<Qmin(i))
     if Q(i)<Qmin(i)
       Q(i)=Qmin(i);
     else
       Q(i)=Qmax(i);
     end
       type(i)=3;
  end
 end
  V(i)=(1/ybus(i,i))*(P(i)-j*Q(i))/(conj(V(i))-sumyv);
  if type(i)==2
  V(i)=pol2rect(abs(Vprev(i)),angle(V(i)));
  end
  end
iteration=iteration+1;
toler=max(abs(abs(V)-abs(Vprev)));
Vprev=V;
end
V
```

Figure 5 Original Gauss-Seidel load flow analysis [22]

The original iteration process in Figure 5 is for a fixed power generation system with fixed load demand. The proposed microgrid system is an unstable power generation with un-controllable load demand in each time step and 24 time steps in total. In order to implement such a system in the iteration process, the Gauss-Seidel load flow programming must be modified.

According to equation (11), the process of computing the admittance bus should be programmed before the Gauss-Seidel iteration process which is shown in Figure 6.

```
function ytest=ytest()
test=test1();
fb=test(:,1);
tb=test(:,2);
r=test(:,3);
% resistance R
x=test(:,4);
% reactance
b=test(:,5);
% ground admitance
z=r+1i*x;
% Z matrix
y=1./z;
% get inverse of each element
b=1i*b;
% make B imaginary
nbus=max(max(fb),max(tb));
nbranch=length(fb);
ytest=zeros(nbus,nbus);
% initialise Ybus
for k=1:nbranch
    ytest(fb(k),tb(k))=-y(k);
    ytest(tb(k),fb(k))=ytest(fb(k),tb(k));
end
for m=1i:nbus
    for n=1:nbranch
        if fb(n)==m || tb(n)==m
            ytest(m,m)=ytest(m,m)+y(n)+b(n);
        end
    end
end
```

Figure 6 Admittance bus calculation programming

Transmission line parameters are input value into the program in Figure 6, and the output value is the admittance matrix. This function will be called for in the iteration process as shown in Figure 7.

```
for t=1:24
 iteration=1;
 toler=1;
 busdata=busdata5();
 V=busdata(:,3);
 Vprev=V;
 p(2)=pv(t);
 p(3)=battery(t);
%        come from decision-making process
 p(4)=DGp(t);
 p(5)=loadP(t);
 Q(5)=loadQ(t);
 Q(4)=DGq(t);
loss=0;
   while (iteration<1000)
     for i=2:nbus
        sumyv=0;
    for k=1:nbus
       if i~=k
     sumyv=sumyv+ybus(i,k)*V(k);
       end
    end
  V(i)=(1/ybus(i,i))*((p(i)-j*Q(i))/conj(V(i))-sumyv);
%   power injected at any bus
     end
    iteration=iteration+1;
    Vprev=V;
   end
     for n=1:4
            fb=linedata(:,1);
            tb=linedata(:,2);
            loss=loss+(((abs(V(fb(n)))-abs(V(tb(n))))/R(n))^2)*(R(n)+j*X(n));
      end
t
loss=real(loss)
vol_mag(t,:)=abs(V)
V
```

Figure 7 Modified Gauss-Seidel load flow analysis

The input value for a modified Gauss-Seidel load flow iteration process consist of the power generated by the PV, battery and backup DG and the real and reactive load power at each time step written in matrixes as well as the initial voltage given to each bus. In order to implement the system in MATLAB programming, power sources except the base DG on the slack bus, are treated as load with negative power consumption. The output value is the bus voltage magnitude and transmission line losses in each time step.

The power generation and load demand are changeable according to the given power and load profile. In section 3.2, a test system is provided for verifying the feasibility of this system.

3.3 Test System Description

In this project, the microgrid is designed for a residential area in order to verify the feasibility of this energy management system. The test MG system is given and the case study results will be analysed and discussed in chapter 4.

The test system is a simplified single phase islanded low voltage microgrid model, consisting of a diesel generator (DG), PV system, battery unit, backup DG and un-controllable load. Figure 8 illustrates the model drawn by DIGSILENT.

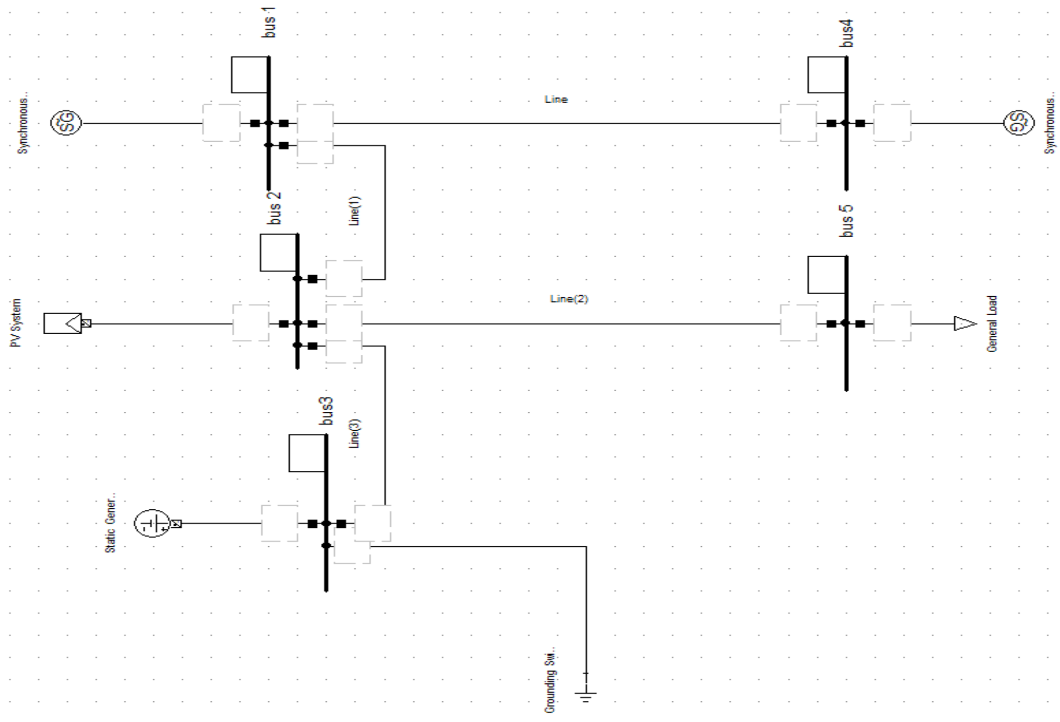

Figure 8 Simplified MG model

Bus type configuration is shown in Table 2.

BUS	**TYPE**
1	Slack bus
2	*PQ*
3	PQ
4	PQ
5	PQ

Table 2 Bus type configuration

In this simplified model, renewable energy resources, backup DG and energy storage system is connected to a PQ bus. When power is generated, it is treated as a negative load.

A detailed description of each device in the system is designed as below.

i.Base Diesel generator (DG): In the proposed microgrid, a DG connected to **bus 1** provides constant power in order to prevent a sudden breakdown in other power generation devices in islanded mode. In the test system, it is assumed that the diesel generator can produce at least 20 kW power. Since the battery capacity in this system is limited, the constant power source is necessary for protecting the system from system failure. The actual size of the base DG can be changed according to the power dispatching result given by the energy management system.

ii. Photovoltaic model: The solar power generation P_S is a product decided by irradiance R_S, the area of the PV panels as given by equation (14):

$$P_S(t) = A_S R_S(t) \quad (14)$$

Equation (14) produces a time series of solar power during a time horizon. On a sunny day, the solar power generation is typically is as shown in Figure 9.

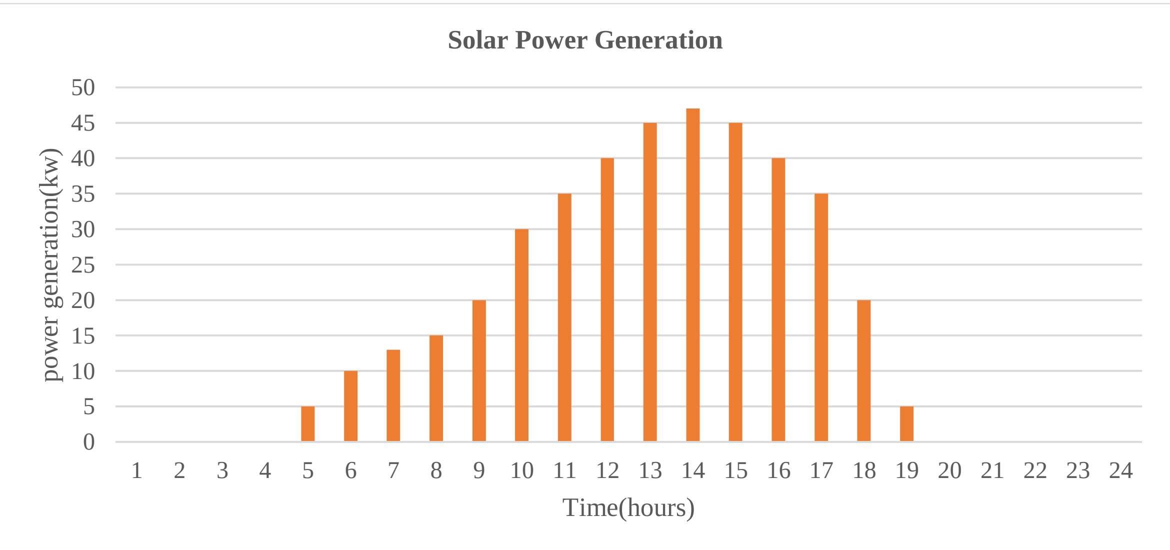

Figure 9 Possible solar power generation in a sunny day

iii.Battery bank model: Equation (15) represents the State of Charge (SOC) of the battery:

$$\mathrm{SOC(t)} = \mathrm{SOC(t-1)} + \int_0^t \frac{1}{C_{bat}} dt \quad (15)$$

The EMS supervises the SOC at every time step. If the SOC is lower than the maximum limit (90% in this system), the excess power is used to charge the battery until the load demand is bigger than the power generation or the battery is fully charged. Under the condition of load demand bigger than power generated by the PV and DG, the battery is charged more than the minimum limitation (20% in this system). Then battery discharge to compensate for load demand. Otherwise, the backup DG is operated. In the proposed energy management system, it is assumed that in the charging process, the battery bank is treated as a positive variable load and in discharging process, the battery unit is treated as a variable negative load. The battery capacity in this system is assumed to be 60 kWh. The battery capacity needs further sizing for different ambient temperature and different amount of solar power generation.

iv. Backup diesel generator*:* Under normal conditions, the backup DG is inactive. However, if the load demand is significantly higher than the power generated by the PV and base DG, and the battery SOC is lower than 20%, then the backup DG will be activated automatically. The main function of the backup DG is to keep the normal operation of the islanded microgrid as well as charging the battery.

v. *Variable load*: In the program shown in Figure 7, the load in the system is different in each time step. In practice, the load demand is decided by customers included in this system. A typical example daily load profile is shown in Figure 10.

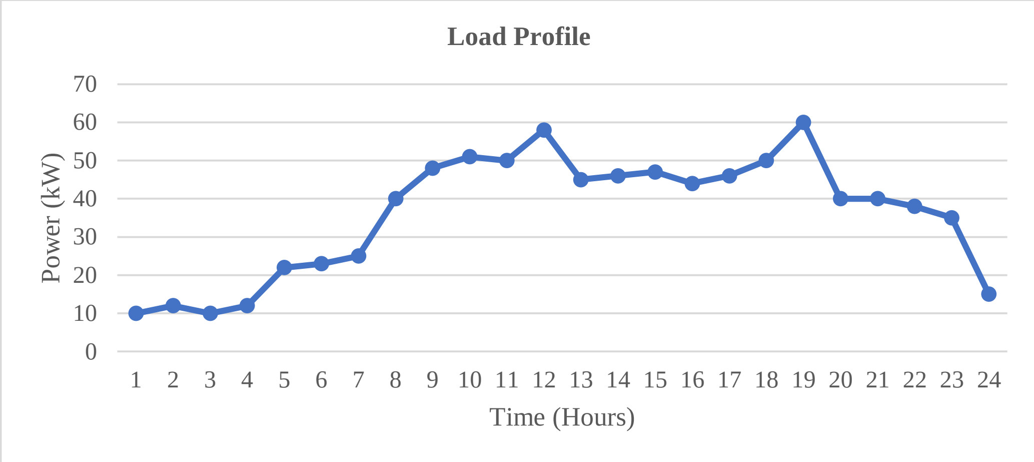

Figure 10 Variable load profile

In practice, the load profile is actually decided by the customer demand. In the test system, the real and reactive load power is used as the input value for the iteration process. As the energy management system focuses on the power dispatch for the islanded microgrid. The reactive power of the loads in this system is for adjusting bus voltage magnitude for the regular operation of the islanded microgrid.

In the test system, the input power data of the PV and load demand in one time horizon is extended into MATLAB as shown below.

$$P_{load} = [P_1, P_2, P_3, P_4, \dots P_t]$$

The selected base value and transmission line impedances is shown in *Table 3*

Base power (Kw)	20
Voltage Base (V)	220
Impendence Base (ohms)	2.42

Table 3 Base values selection

from	to	R(ohms)	X(ohms)	R(p.u)	X(p.u)
1	2	0.121	0.29	0.05	0.2
1	4	0.242	0.58	0.1	0.3
2	5	0.0484	0.117	0.02	0.1
2	3	0.121	0.29	0.05	0.2

Table 4 Selected transmission line parameters

In the program shown in Figure 4, the input value is the power generated by photovoltaic system and the base DG, as well as the real load power consumption. The output result is shown in the command window. For example, at t time, the battery state of charge, the battery power consumption or generation, and the dump load power consumption.

The given transmission line parameters for computing the admittance matrix is shown in Figure 11.

```
function linedata=linedata4()
linedata=[1 2 0.05 0.2
          1 4 0.1 0.3
          2 5 0.02 0.1
          2 3 0.05 0.2];
end
```

Figure 11 Line data programming

From the program given in Figure 6, the admittance matrix result is shown in Figure 12.

```
ans =

   2.1765 - 7.7059i  -1.1765 + 4.7059i   0.0000 + 0.0000i  -1.0000 + 3.0000i   0.0000 + 0.0000i
  -1.1765 + 4.7059i   4.2760 -19.0271i  -1.1765 + 4.7059i   0.0000 + 0.0000i  -1.9231 + 9.6154i
   0.0000 + 0.0000i  -1.1765 + 4.7059i   1.1765 - 4.7059i   0.0000 + 0.0000i   0.0000 + 0.0000i
  -1.0000 + 3.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   1.0000 - 3.0000i   0.0000 + 0.0000i
   0.0000 + 0.0000i  -1.9231 + 9.6154i   0.0000 + 0.0000i   0.0000 + 0.0000i   1.9231 - 9.6154i
```

Figure 12 Admittance matrix

The admittance matrix and the power generation/consumption values of each part of the microgrid system, including PV power, battery power, backup DG active/reactive power, load reactive and active power are used as the input value of the Gauss-Seidel iteration. Process program presented in Figure 7.

In each time horizon, one element is taken from each matrix. For example, at the first time step, the PV power is 0, the battery is in charging mode, absorbs power of 0.5 p.u, the backup DG is inactive, the load real power and reactive power is 0.5 and 0.25 respectively. As a result, the selected power from each bus for the first step is [1, 0, 0.5, 0, 0.5]. Then, applying this matrix to the iteration process, the bus voltage and power are computed as shown in Figure 7.

The output value of the modified Gauss-Seidel iteration process program is described as “at t time, the voltage magnitude on each bus and the transmission line losses in the microgrid. In each time step, the transmission line power losses and bus voltage magnitude are given by the program running in Figure 7. The bus voltage magnitude matrix illustrates that whether the microgrid system has over-voltage problems, all the bus voltage magnitudes should be within the standard limit $\pm10\%$ at each time step for a well-performed electrical network. On the other hand, the bus voltage predicts the power dispatch variation trend from the variation of voltage magnitude from each time step.

In order to verify the performance of this programming system, four case studies under different given power and load profile are analysed and discussed in the next chapter.

Chapter 4: Results Analysis and Discussion

The proposed microgrid system (Figure 8) is a simplified model of an islanded microgrid network with solar photovoltaic and an energy storage system. The main function of the energy management system is to optimise power dispatch and to balance the power flow inside the system in islanded mode, as well as leaving reserve capacity for the system. In order to verify the performance of the proposed EMS, the test system is operated under different load profiles and solar power generation. The case study overview is listed below.

Case 1: The test-system is operated in the summer season with high solar power generation and high load demand.

Case 2: The test-system is operated in the winter season with low solar power generation and high load demand.

Case 3: The test-system is operated in the spring season with high solar power generation and low load demand additionally, there is a sudden disconnection from the photovoltaic system.

Case 4: The test-system is operated under high solar power generation and low load demand during but the day is cloudy.

The organized test results and discussion will be shown in the next section.

4.1 Case study 1: Clear summer day

In this case, a system with high solar power generation and high load demand are concluded. The photovoltaic system power generation result from a sunny summer day and the provided load profile is shown in Figure 13.

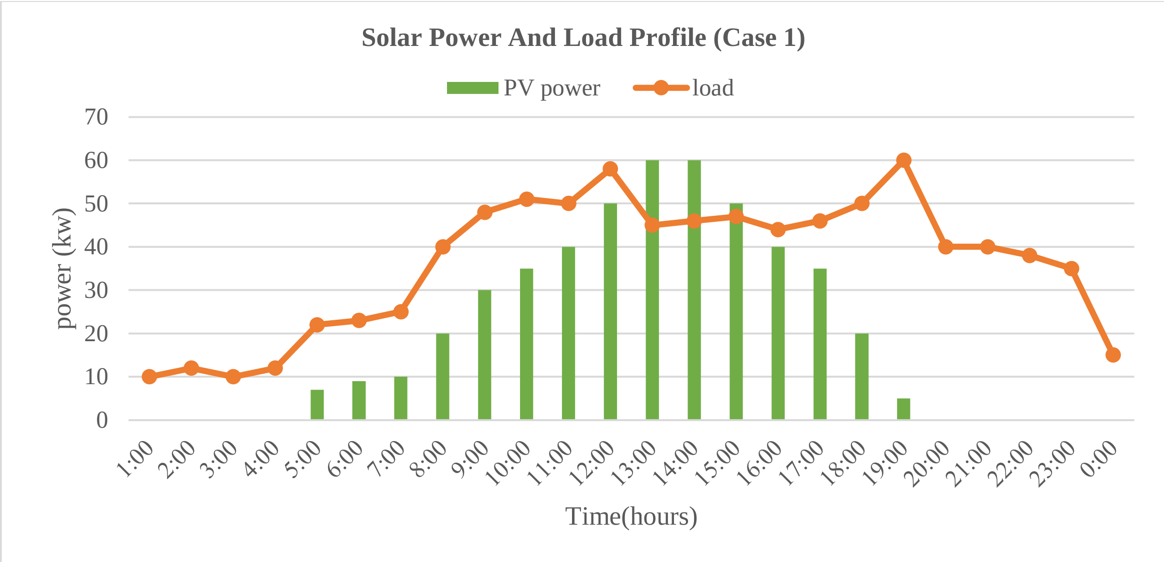

Figure 13 Solar power profile and load profile (case 1)

Applying the solar power generation and load flow data for the decision-making process by programming into MATLAB, the battery power data is shown in Figure 14.

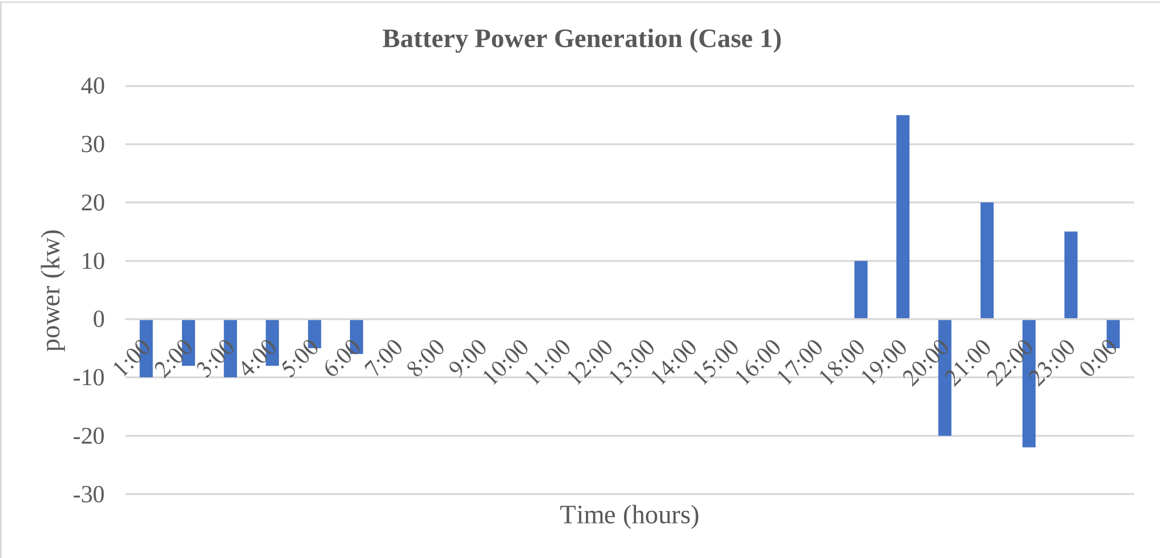

Figure 14 Battery power input data (case 1)

The bus voltage result given by the operation of Gauss-Seidel load flow analysis is shown in Figure 15.

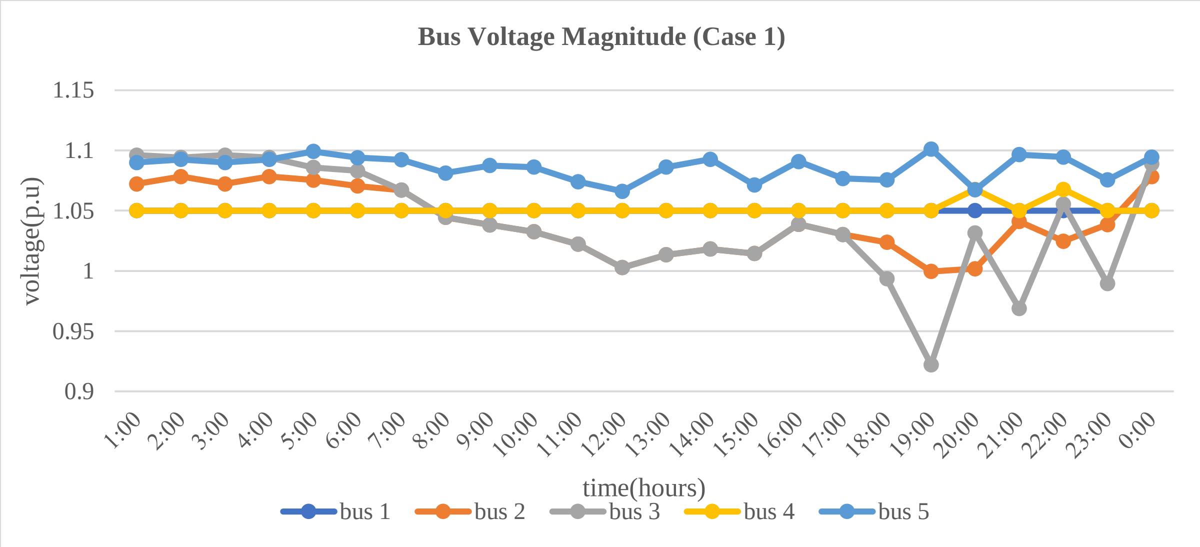

Figure 15 Bus voltage (case 1)

The plot of the bus voltage verifies the system is well-operated, within the standard voltage magnitude limit of $\pm$ 10%. From the figure it is evident that there is no over-voltage or low voltage problem in the proposed system in this islanded microgrid. At 19:00, the load demand is at peak value, the battery discharging power is to compensate for the load demand, so the voltage on bus 3 reach the lowest value.

The power dispatch result is shown in Figure 16.

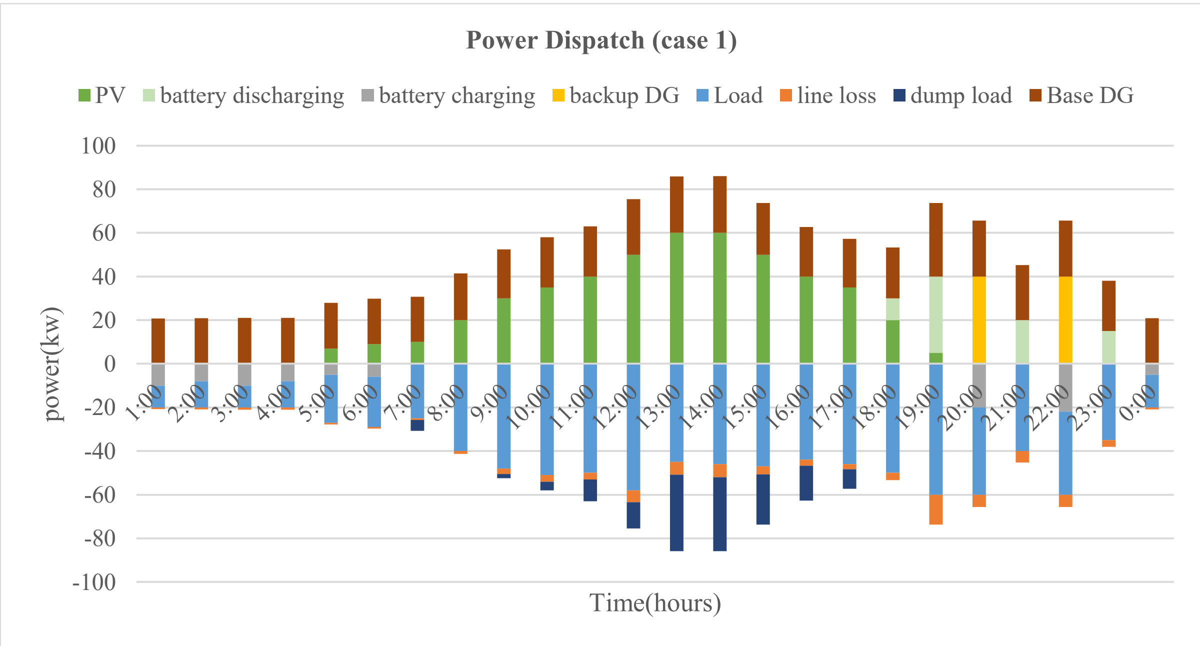

Figure 16 Power dispatch (case 1)

The figure above shows the power balance and power dispatch of the network. However, during the summer season the solar power is sufficient, the excess power dissipated to the dump load is higher especially at 13:00 and 14:00.

The power generation and consumption comparison results are shown in Figure 17.

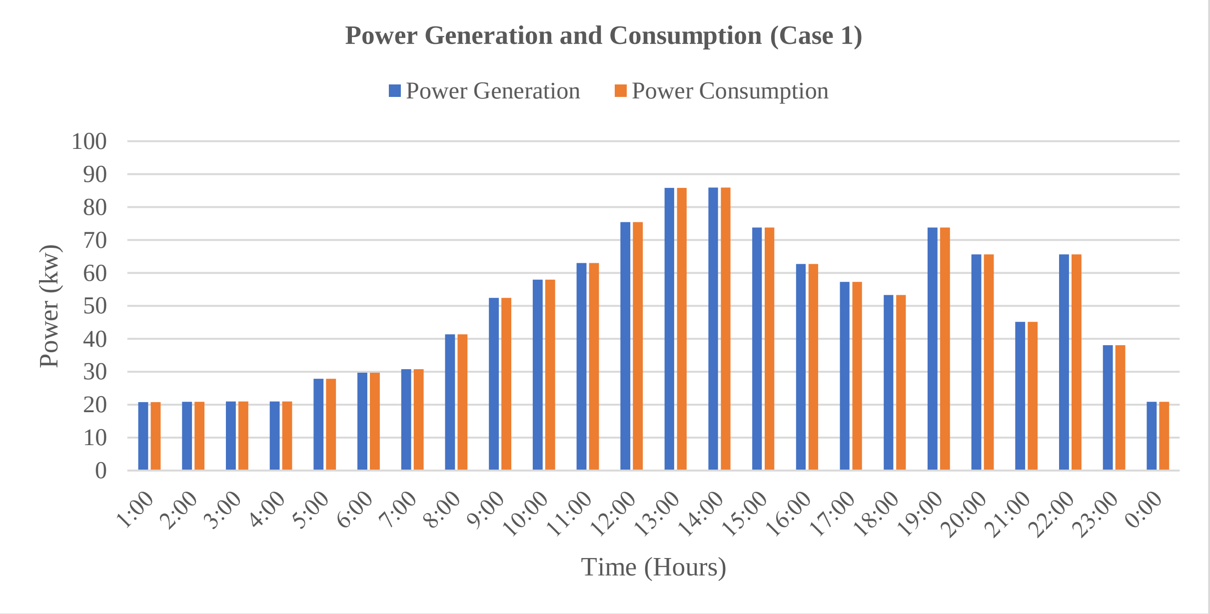

Figure 17 Power generation and consumption comparison (case 1)

The total power generation equals to the total power consumption at each time step. The microgrid energy management system controls the power dispatch effectively. Figure 18 and Figure 19 shows the power generation from different sources in 24 hour-period and only daytime (6:00-18:00) respectively.

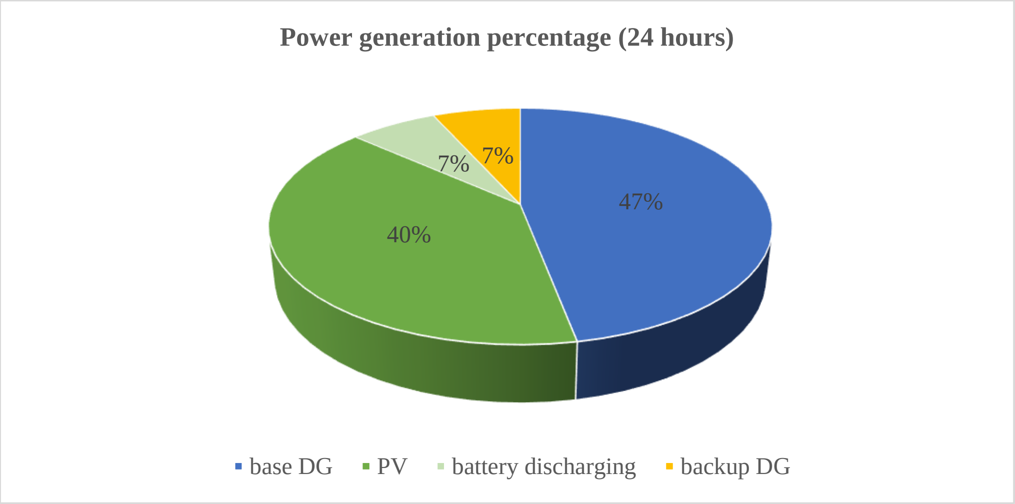

Figure 18 Power generation percentage in 24 hours (24-hour)

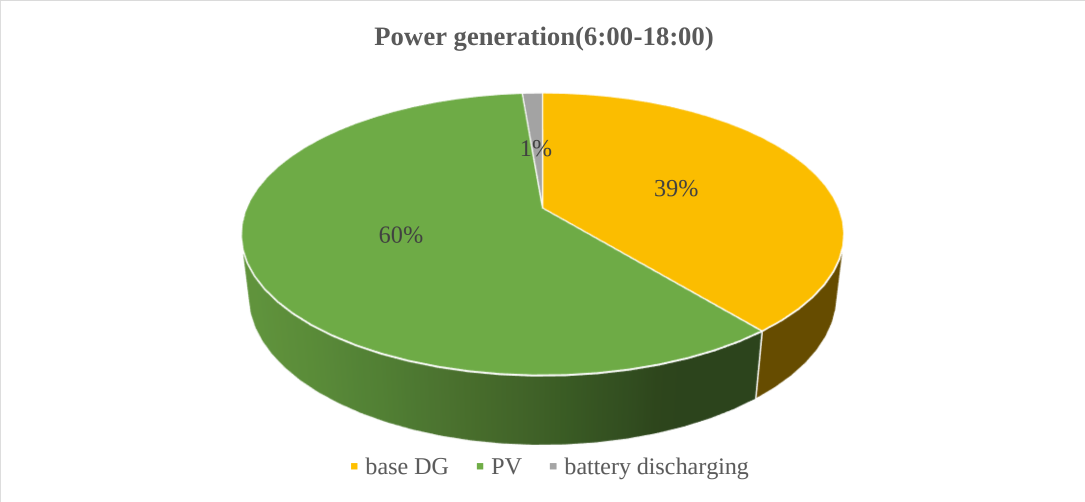

Figure 19 Power generation percentage (daytime)

In the daytime, power generated by battery discharging accounts for only 1%. This is evident that solar power generation and the base DG can satisfy the load demand. The solar power accounts for most of the power generation in the daytime around 60%. However, for the peak load demand in the night time, the backup DG and base DG are both responsible for the power dispatch.

The power consumption percentage for Case 1 is shown in Figure 20.

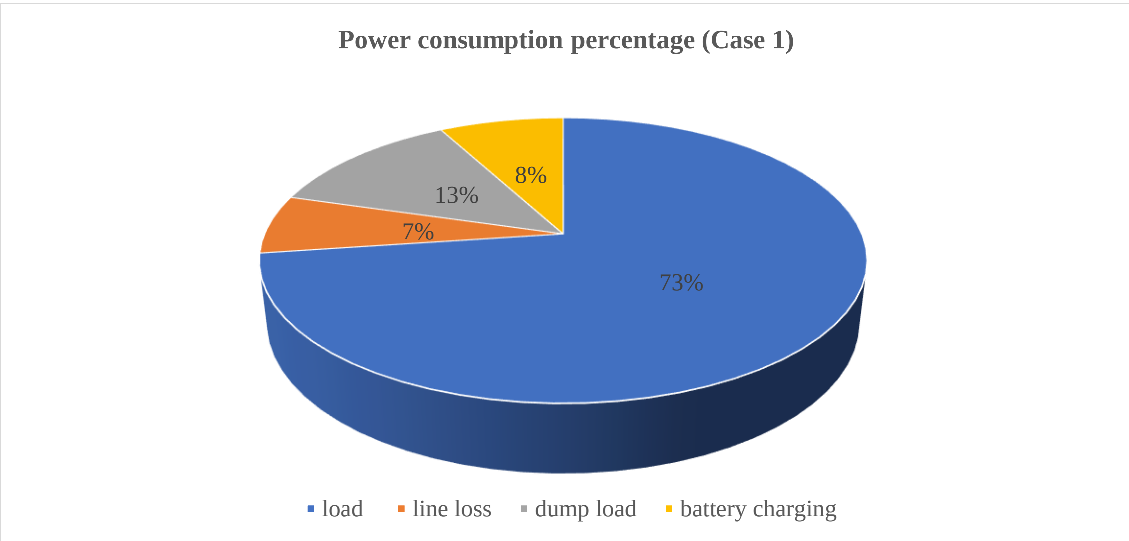

Figure 20 Power consumption (case 1)

According to the three pie charts listed above, the battery and backup DG is treated as standby power sources because the solar power is sufficient to satisfy the load demand. The battery only discharges during the night time combined with the backup DG when there is no solar power during night time. On the other hand, from the power consumption percentage chart and power dispatch chart, from 10:00 to 17:00, the battery is fully charged according to the battery state of charge as shown in Figure 21. In this case, the excess power is dissipated to the dump load, accounting for 13% of the power consumption amount. From the chart, it is clear that the power generated by generators satisfying the load demand as well as charging the battery for the next time horizon. The state of charge curve of the battery is shown in Figure 21.

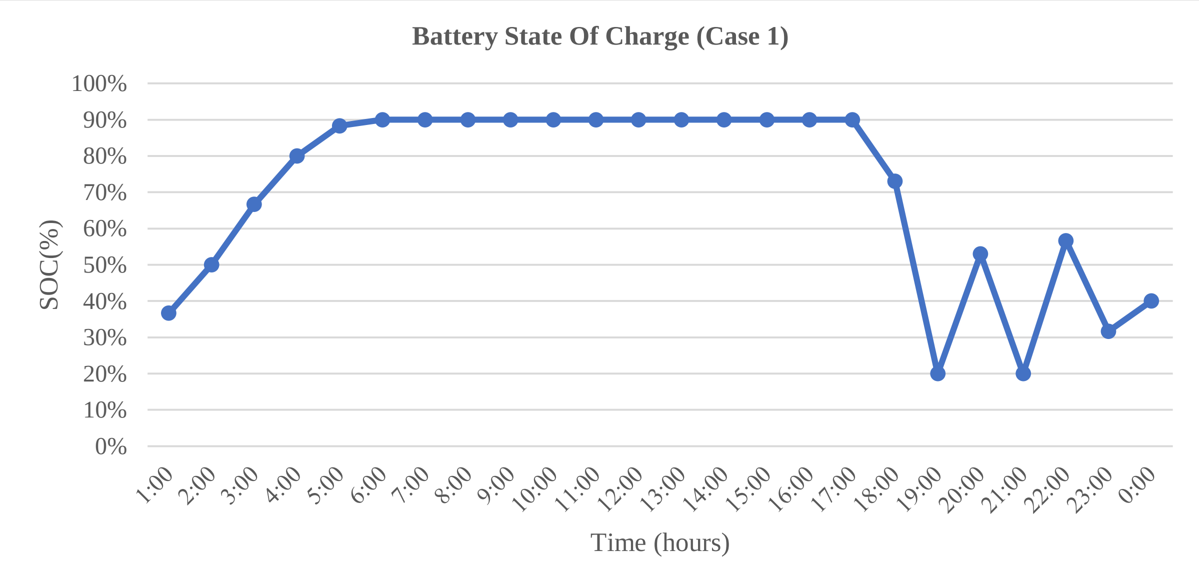

Figure 21 Battery state of charge (case 1)

The battery starts with 20% state of charge at the beginning of the day. The case is under the high solar power generation and high load demand condition. From the figures listed above, the peak load demand appeared at two points. One is in the middle of the day around 11:00 to 12:00, and the other one is in the night time, around 19:00 to 20:00. For the first peak load demand period, as there is sufficient solar power generation in the middle of the day, the peak load can be satisfied completely by the photovoltaic system power generation. The backup DG and battery bank is used as the standby power sources in case of any higher load demand condition or photovoltaic breakdown condition. However, for the second peak load demand from 19:00 to 20:00, the energy management system dispatches the battery discharge power and backup DG power to satisfy the load consumption as the solar power generation is zero at night time.

The energy management system optimises the power dispatch by dissipating the excess power to charge the battery bank at the beginning of the day. Based on the power dispatch condition, it is estimated that the maximum power generation of the diesel generator is around 33 kW, which helps to size the generator before the installation of the microgrid.

The battery bank is charged to “full condition” from 5:00 to 17:00, and discharges for the high load demand period during night time and charged to full again, getting prepared for the next day. Enough reverse capacity is left for the next period in case of emergency as the battery is fully charged in most of the time during the day. However, in summertime, it can be seen from Figure 18, Figure 19 and Figure 20, during the daytime, the solar power is sufficient enough. As a result, from Figure 19, it is clear that solar power is the main power generation device from 6:00 to 18:00, charging the battery and satisfying the load demand. During night time, when the second peak load appeared, the fully-charged battery bank and backup DG compensate for loads. However, the dump load power consumption can be decreased by increasing the battery capacity to store more power.

According to the bus voltage magnitude figure (Figure 15), the system is successfully operated with all the bus voltage magnitudes are within the $\pm$ 10% limit. The bus voltage magnitude variation illustrates the power balance among the various generation devices. As the load demand increased, the voltage on the load bus increased, where the voltage on other buses decreased.

The energy management system effectively maximizes the power generated by the photovoltaic system in the daytime. During the 24-hour time horizon, the solar power generation and slack bus diesel generator account for most of the power generation, around

87%, and battery discharging and the backup diesel generator account for 13%. According to the battery SOC chart, for most of the time during the day, the battery is fully charged because of the amount of power supplied by the photovoltaic, the excess power is wasted to the dump load during the daytime.

From the test result showed above, it can be concluded that during the summer period, the proposed energy management system can successfully manage the power dispatch process for the islanded microgrid system. The power generated by various devices is balanced in the microgrid. In this case, the system has enough reverse capacity due to the battery bank and backup DG in case of emergency.

4.2 Case study 2: Winter season

In the second case study, it is assumed that during the winter condition, the solar irradiance is less than in the summer as the daylight is shorter than in summer. Figure 22 shows the load profile and solar power generation.

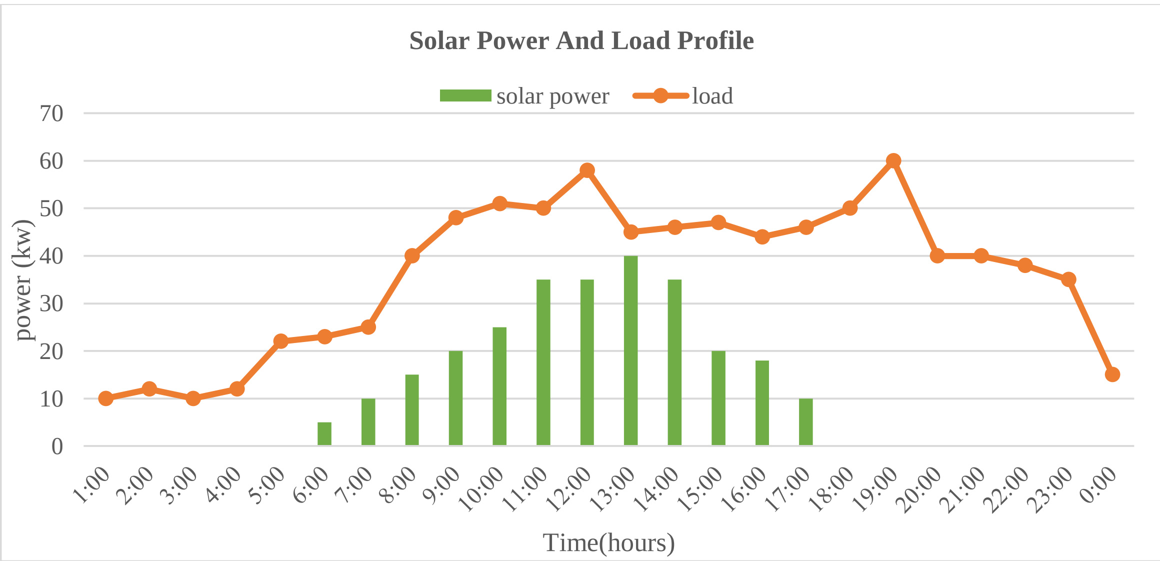

Figure 22 Solar power generation and load profile (case 2)

During the winter season, the load demand is assumed to be the same as in case study 1. However, the solar power generation decreases with only 40 kW at the peak value. On the other hand, compared with the summer period, the photovoltaic panels start to generate power is later in the day compared with the summer period.

The battery power generation is shown in Figure 23.

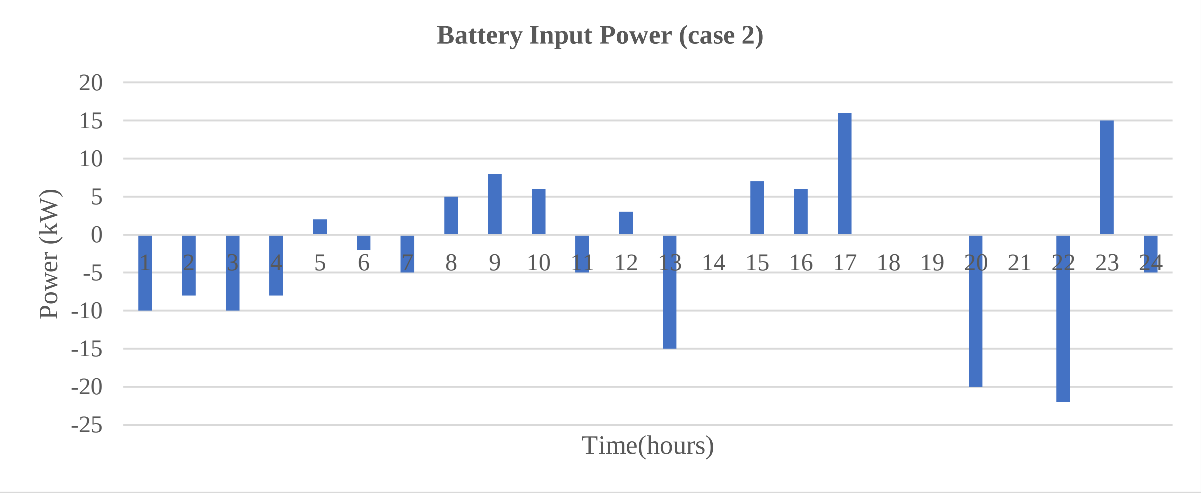

Figure 23 Battery power generation (case 2)

In this case, the battery takes part in the power dispatch much more compared with that in the summer period, since the solar power is not sufficient to compensate for the load demand during the daytime. Under this circumstance, the battery discharges from 8:00 to 10:00 and 15:00 to 17:00.

The bus voltage magnitude result is shown in Figure 24.

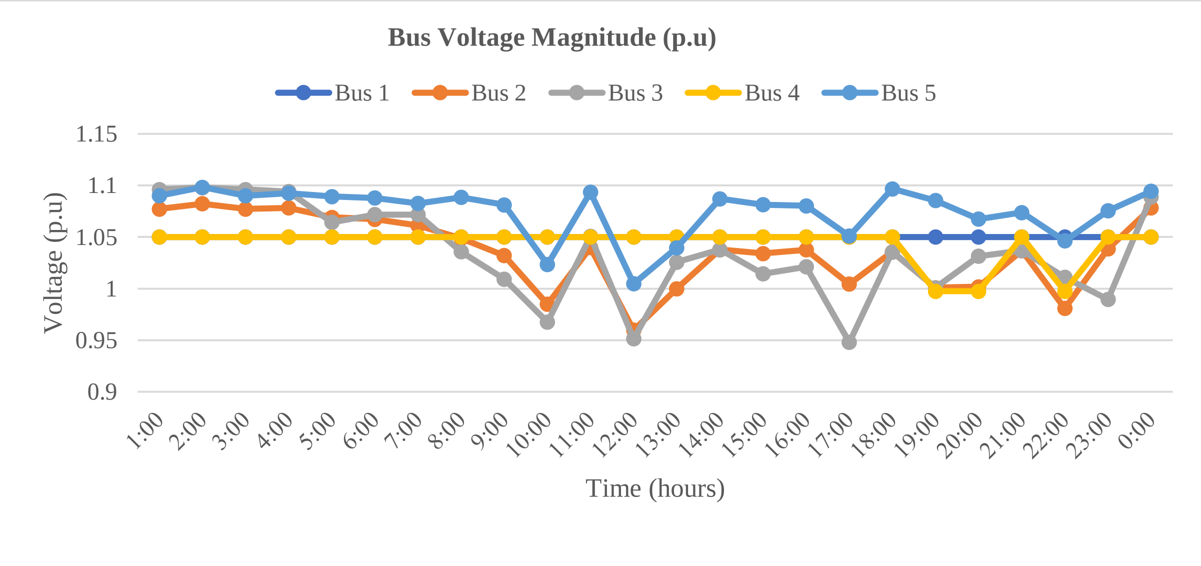

Figure 24 Bus voltage magnitude (case 2)

The bus voltage magnitude is within the standard limit. As the load demand varies at each time step, the voltage magnitude on each bus changes, illustrating the power flow in the microgrid. From the chart, it can be seen that the backup DG at bus 4 operates three hours in total. However, at 23:00, the bus 5 voltage magnitude is slightly over 1.1 p.u. The possible reason is that the battery discharging at 23:00 and the load cannot consume all the power produced by the battery bank.

The power dispatch is shown in Figure 25.

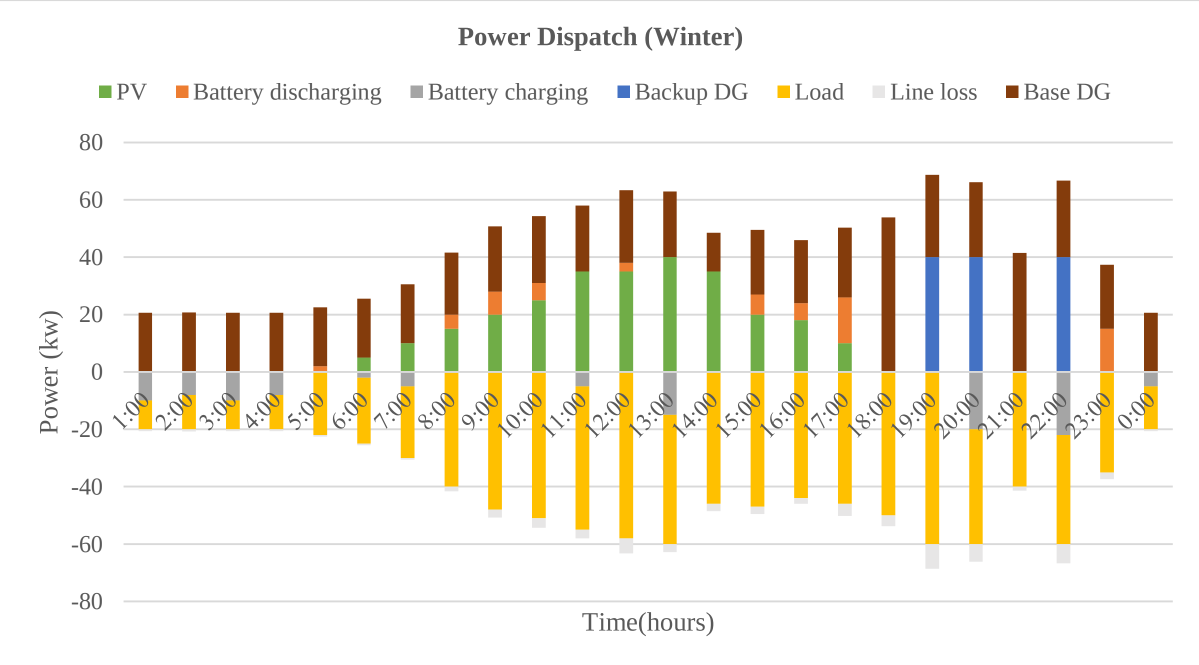

Figure 25 Power dispatch (case 2)

Since the solar power is not sufficient during the winter time, so the power generated by the photovoltaic system is used to charge the battery or satisfy the load completely in every hour. As a result, there is no power dissipated to the dump load during winter time. On the other hand, the backup DG operates three hours in this case. The power generation percentage pie chart is shown in Figure 26.

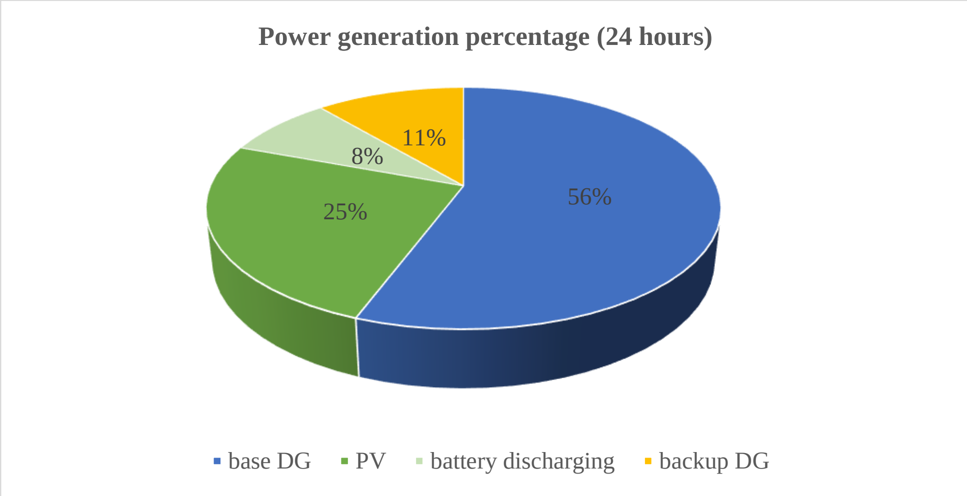

Figure 26 Power generation percentage (case 2)

Comparing the figures of power generation percentage from the two different seasons, it is clear that the solar power generation is less in winter, and the load demand is the same as in case one, where the battery is discharged more in order to satisfy the load demand. The power generation percentage during the daytime is shown in Figure 27.

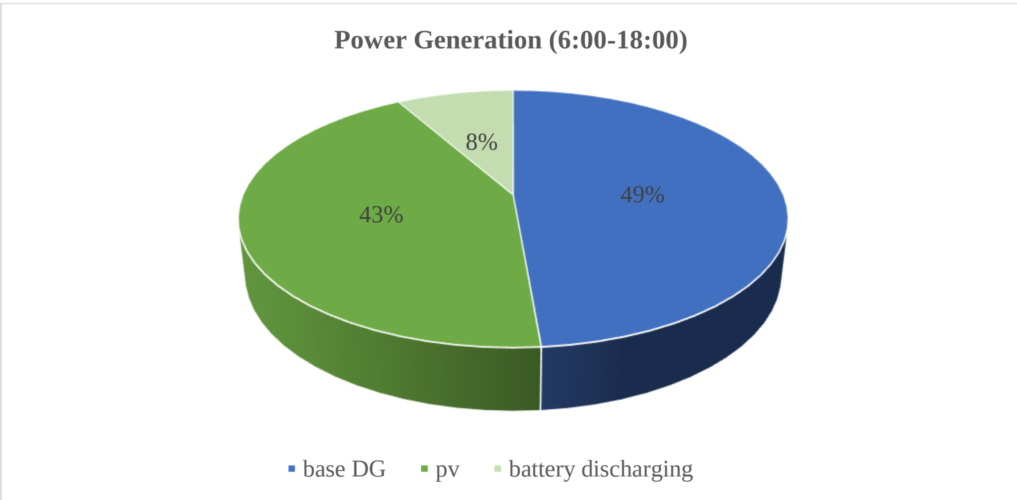

Figure 27 Power generation percentage (daytime)

Although the solar power is not high during the winter time, it can account for 43% in the day time if the weather is sunny enough. The battery discharging power accounts for 8%, and the system relies on base DG generation in the daytime.

The power consumption percentage is shown in Figure 28.

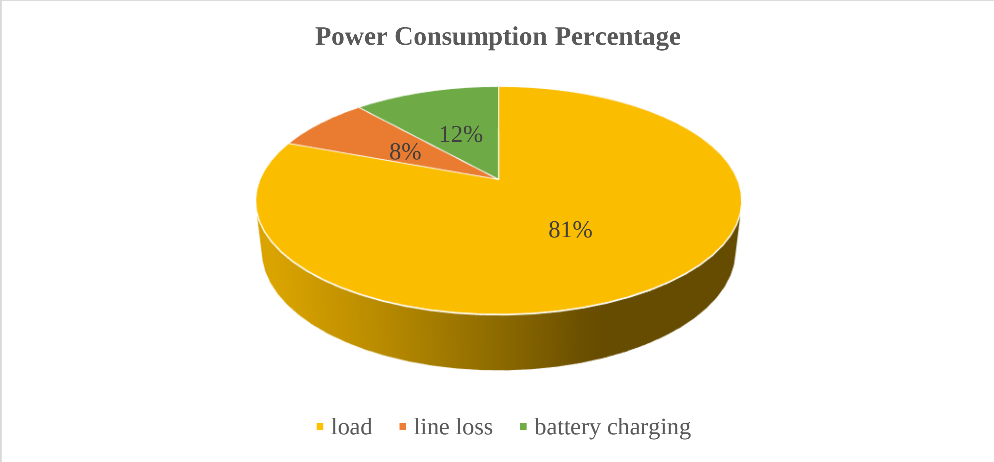

Figure 28 Power consumption percentage (case 2)

Compared with case one, the power used for charging the batteries increased in this case. And there is no dump load consumption, as all of the power generation is completely used.

The battery state of charge is shown in Figure 29.

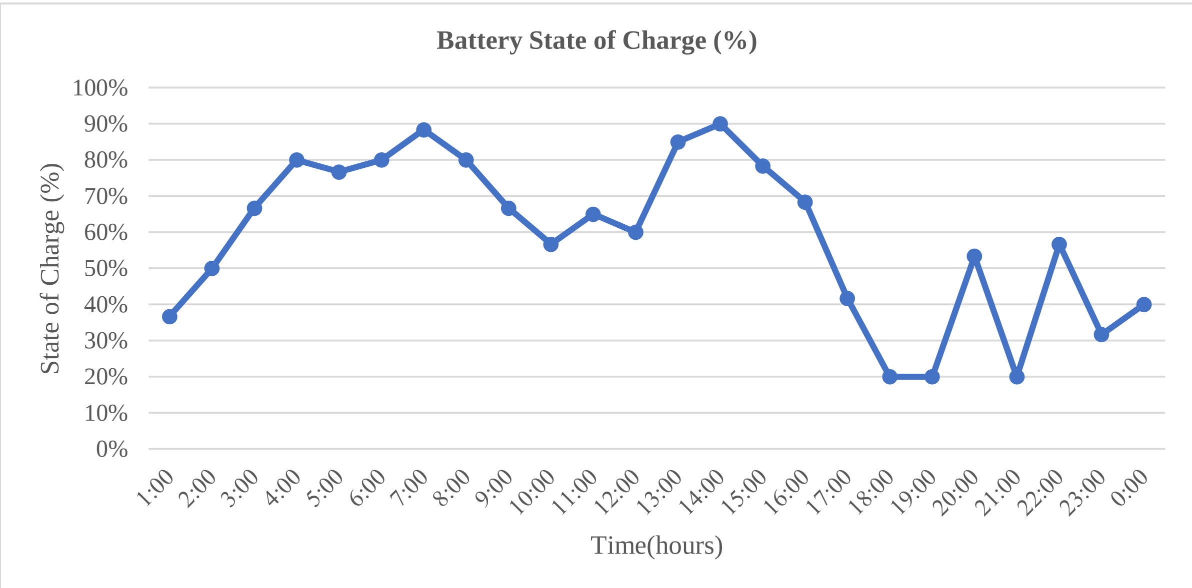

Figure 29 Battery state of charge (case 2)

From the figures above all, the battery is no longer used as a standby power sources in this case. This is due to the fact that there is insufficient solar power generation during the daytime, then the EMS dispatched battery power to satisfy the load demand until the battery is discharged to below 20% SOC. The backup DG operated at 18:00, 19:00 and 21:00. In this case, there is no dump load power consumption.

From the power dispatch figure, the base DG capability is higher compared with the summer case. In the winter case, the base DG should have maximum power generation at 55 kW.

However, from the environment-friendly point of view, the backup DG operation has a negative effect on the environment. On the other hand, the operation of the backup DG adds extra cost to the operation cost compared with case one. The battery in this case should have a bigger capacity compared with the battery in case 1.

4.3 Case study 3: Spring season

In this case, the load demand is lower than the last two cases, but from 11:00 to 12:00, there is a sudden disconnection from the microgrid. The result shows how the energy management system reacts to this accident. The solar power profile and load profile is shown in Figure 30.

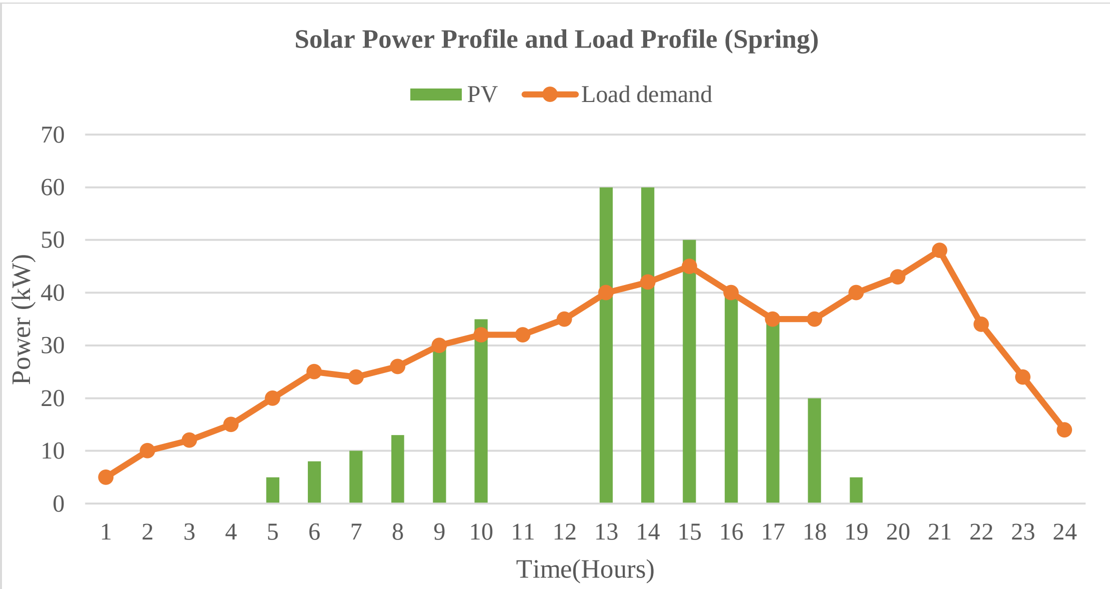

Figure 30 Solar power profile and load profile (case 3)

The battery power generation is shown in Figure 31.

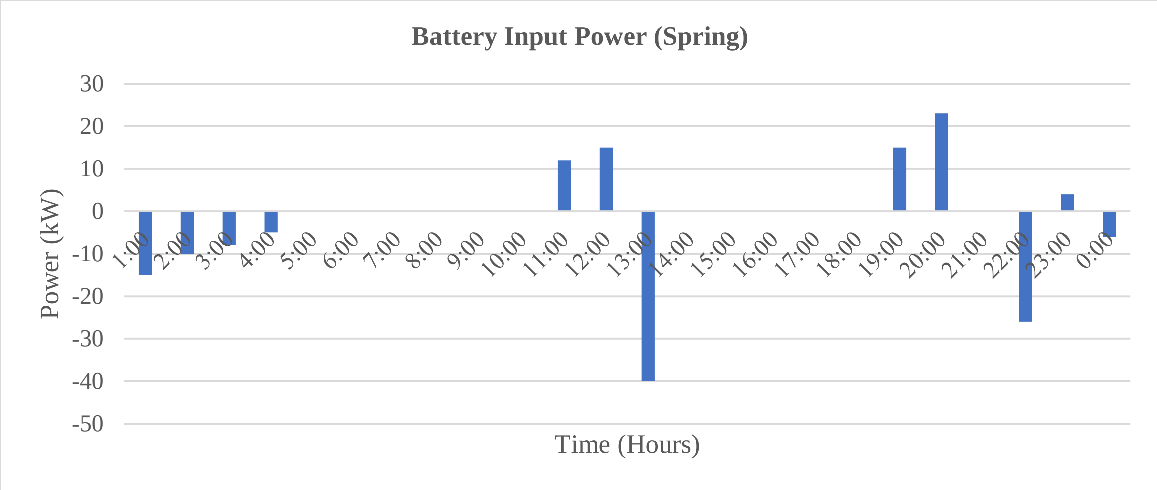

Figure 31 Battery power generation (case 3)

It is similar to case one in that the battery is fully charged from 5:00 to 10:00 and discharged at night time when the peak load demand appeared. However, from 11:00 to 12:00, the photovoltaic system breaks down and is disconnected from the microgrid system. The battery is discharged at this time until the photovoltaic system returned to services.

The battery state of charge at each time step is shown in Figure 32.

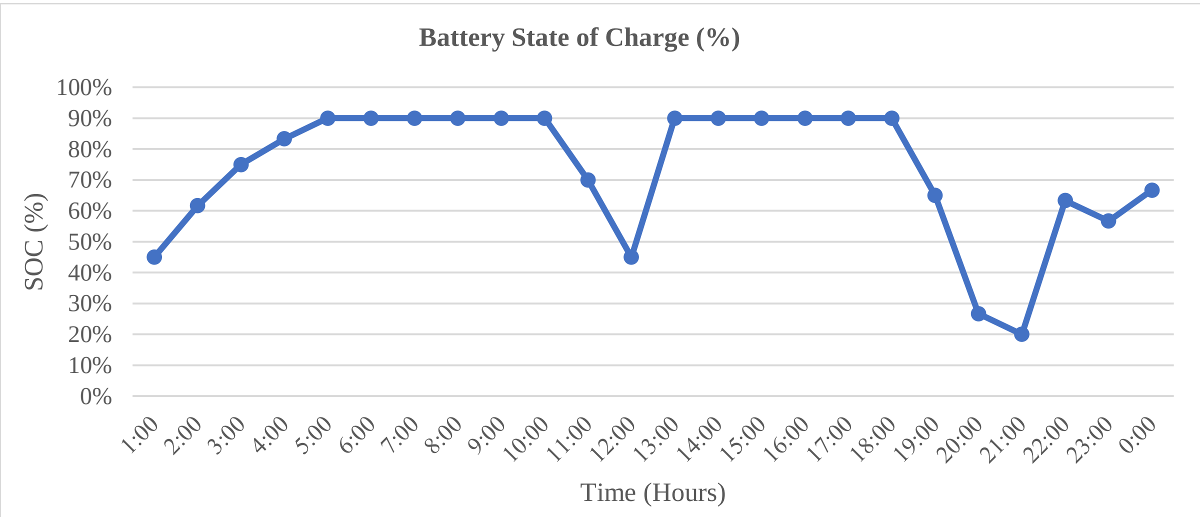

Figure 32 Battery state of charge (case 3)

The battery starts with 20% at the beginning of the day and is charged to 90% at 5:00. From 11:00 to 12:00, the battery is discharged to 40% and then was charged back to 90% at 14:00. The battery stayed at 90% state of charge until 18:00. The battery discharged again from 18:00

to 22:00 until the SOC reached the allowable minimum SOC value. From 21:00 to 22:00, the battery is charged again by the backup DG. The bus voltage data is shown in Figure 33.

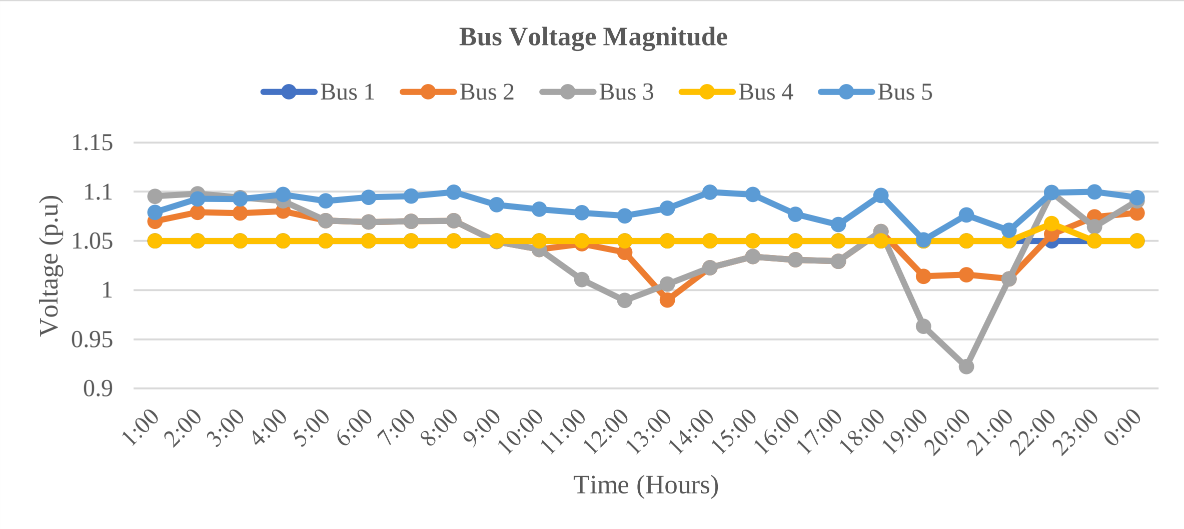

Figure 33 Bus voltage magnitude (case 3)

From the figure above, it illustrates that the system is performed well with all the bus voltages within the standard at each time step. As the load bus voltage varies at each time step, the voltage magnitude on bus 2 to bus 4 varies as well in order to avoid over-voltage problems. At 20:00, the bus 3 voltage decreased to between 0.9 p.u to 0.95 p.u. The reason is the battery is discharging at this time and the load demand is very high. In order to keep the system balanced, the bus 3 voltage decreases to the lowest point.

The power dispatch chart is shown in Figure 34.

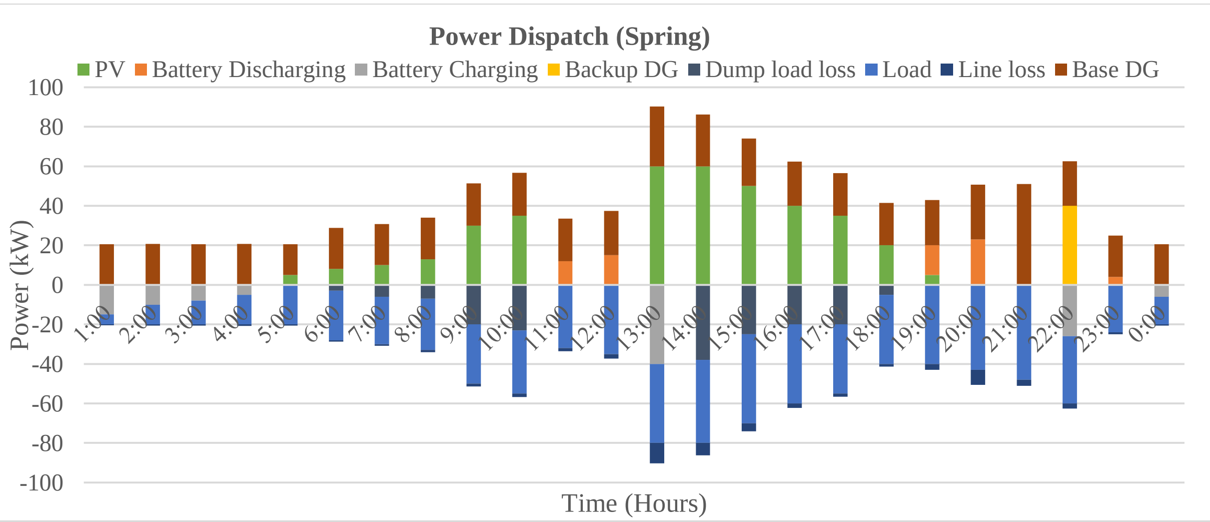

Figure 34 Power dispatch (case 3)

From the figure, the maximum power generation of the base DG is around 51kW at 21:00.

Since the solar power is high in this case, the solar power is the main power source for compensating the load demand except at 11:00 and 12:00 when the photovoltaic system is suddenly disconnected from the power grid. The EMS manages to dispatch battery discharging power for this sudden accident. After the photovoltaic system went back to service, the battery is fully charged again. The EMS dispatched the backup DG power at 22:00 for the peak load demand.

The power generation percentage is shown in Figure 35 and Figure 36.

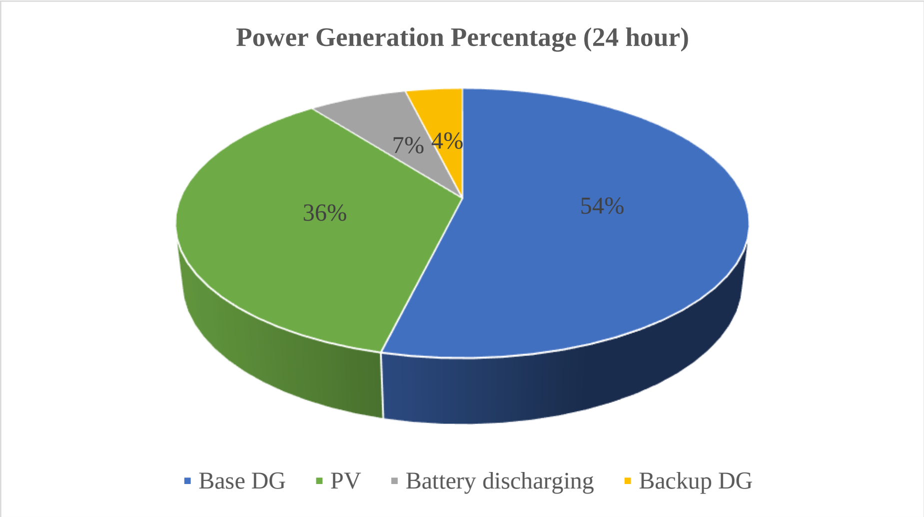

Figure 35 Power generation percentage (24-hour)

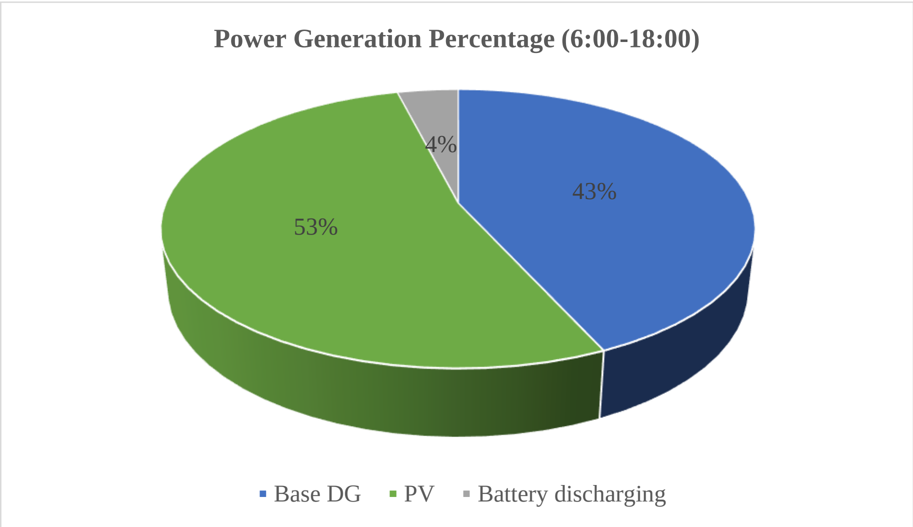

Figure 36 Power generation percentage (daytime)

Power consumption percentage is shown in Figure 37.

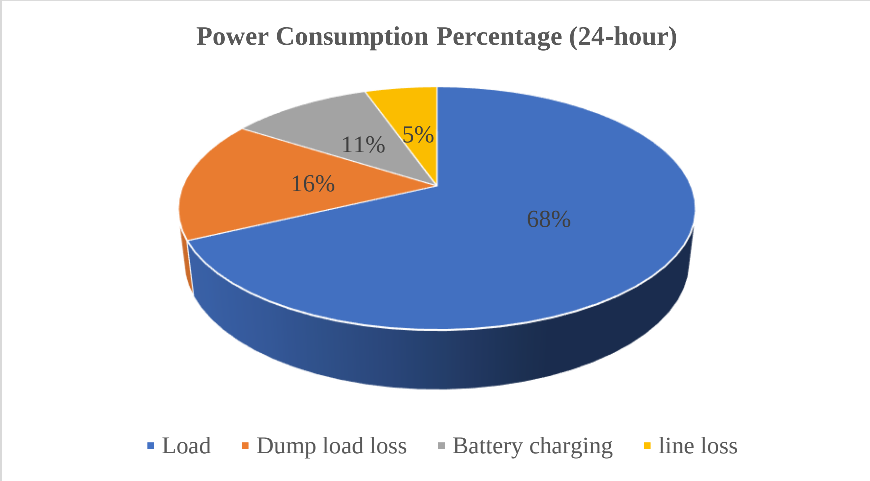

Figure 37 Power consumption percentage (case 3)

From the power generation and consumption percentage figures (Figure 26, Figure 27and Figure 28), the photovoltaic system power generation accounts for 53% during daytime, and the base DG accounts for only 43%. Although there was a breakdown in the photovoltaic system, the solar power generation percentage still accounts for more than half of the daytime power generation.

In this case study, the solar power is sufficient during most of the daytime, when the EMS dispatches more solar power at daytime, and the load demand is compensated by battery discharging power and the backup DG at peak load moment during the night. From 11:00 to 12:00, the solar power is zero, the energy management system reacted to this accident by dispatching battery power during this time until the PV system went back to normal at 13:00.

Compared with the summer and winter cases, this test focused on the self-protection capability of the islanded microgrid. When a sudden accident takes place at a certain time step, the energy management system keeps the constant power supply by dispatching power generated by other sources, avoiding system failure. The battery in this case is capable of compensating the load demand when the sudden breakdown occurred

Besides the grid-protection test in this case, from the figures in this case (figure 33 to figure 40), the energy management system effectively balanced the various distributed energy resources at each time step.

4.4 Case study 4: Cloudy day

In this case, the system is tested in a cloudy day. The solar power profile and load profile is shown in Figure 38.

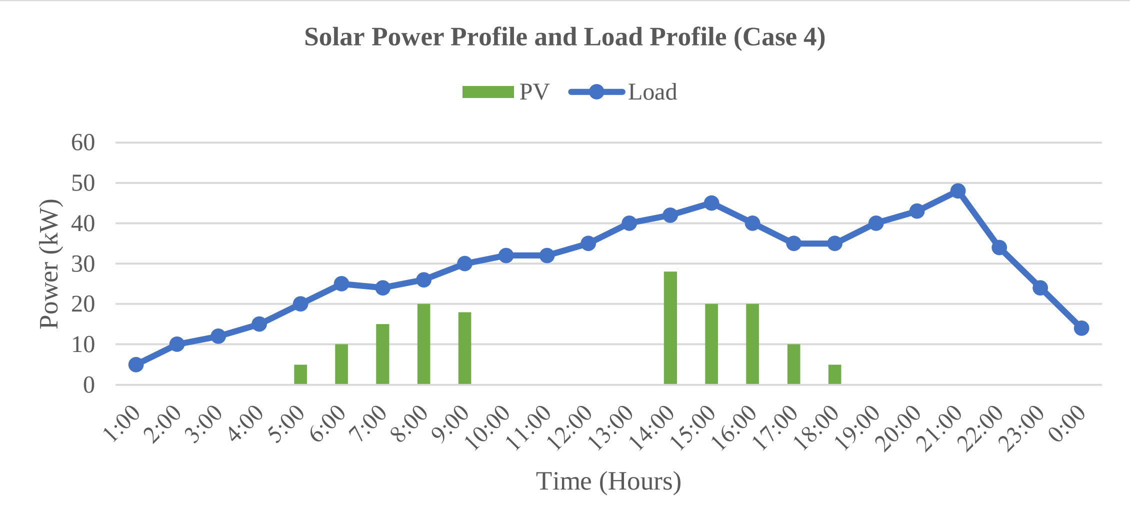

Figure 38 Solar power profile and load profile (case 4)

From 10:00 to 13:00, the solar power generation is zero due to the cloudy weather. For comparison, the selected load profile is the same as case 3.

The battery input power is shown in Figure 39.

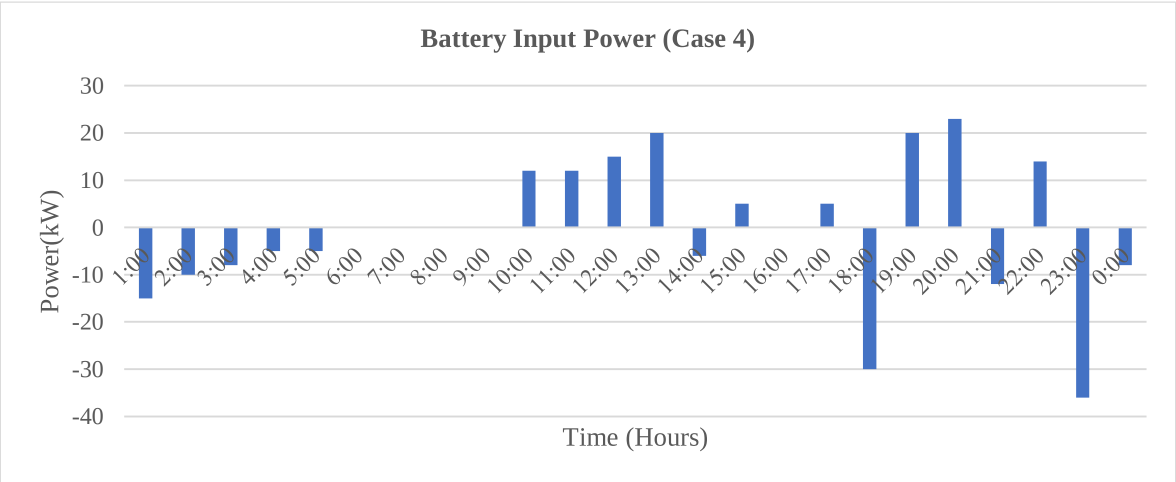

Figure 39 Battery Input Power (case 4)

According to the battery input power, the load profile and the solar power profile, the battery state of charge at each time step is shown in Figure 40.

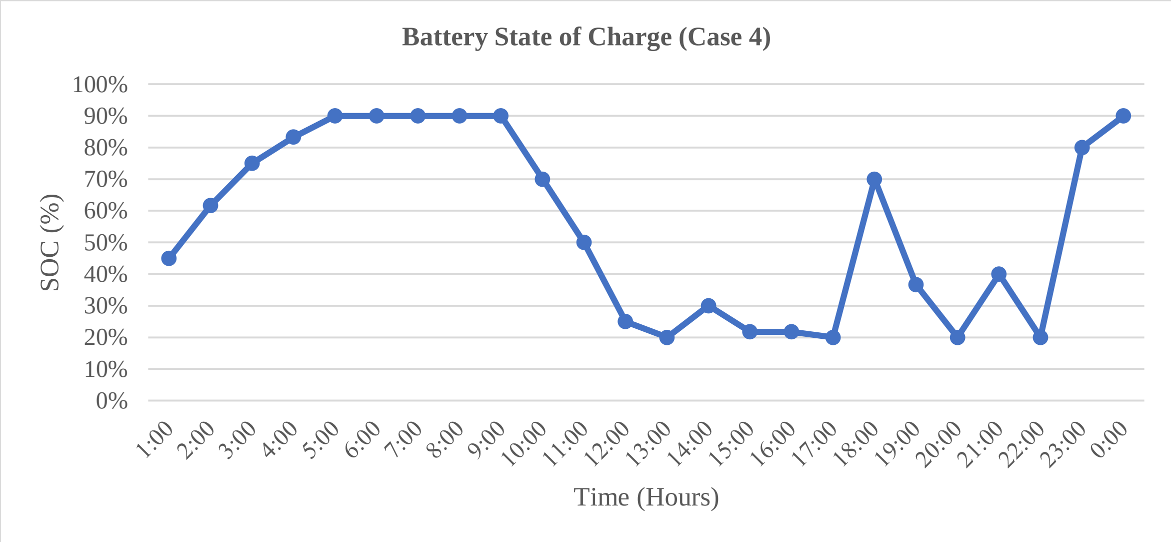

Figure 40 Battery State of Charge (case 4)

The battery is charged and kept in the fully-charged until 9:00. Then the battery discharged to 20% state of charge to compensate the load demand from 9:00 to 12:00. When the backup DG operated at 18:00, 21:00 and 23:00, the battery is charged again. By the end of the day, the battery is full-charged.

The voltage magnitude on each bus at each time step based on the iteration process is shown in Figure 41.

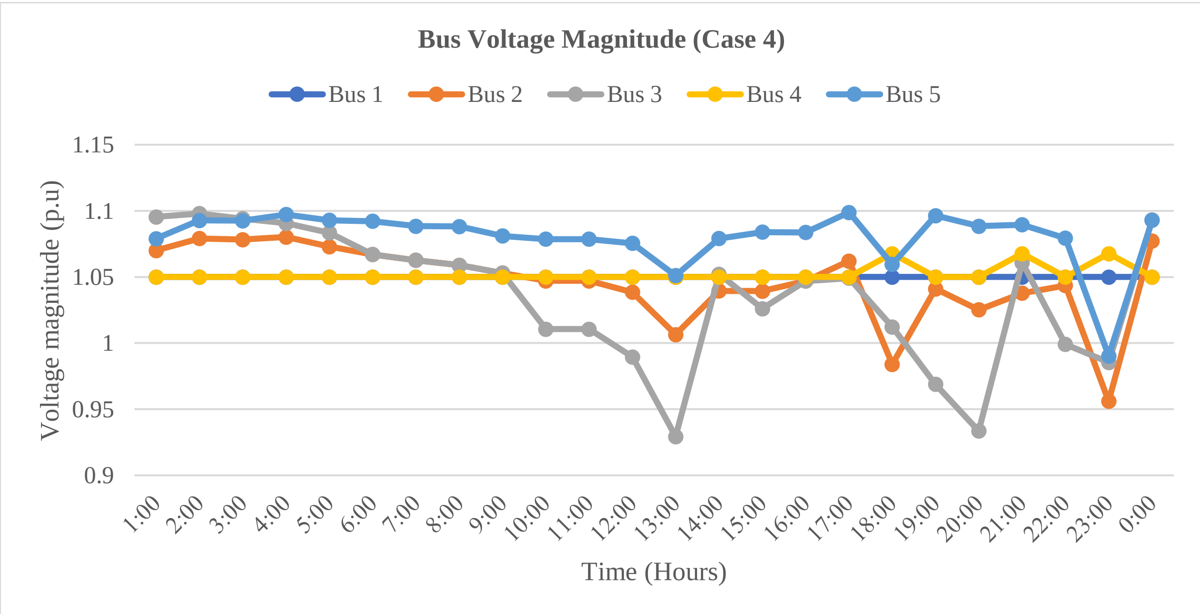

Figure 41 Bus voltage magnitude (case 4)

The bus voltage magnitude at each time step illustrates the system is well-operated with all the bus voltage magnitude within the standard. From 13:00 to 14:00, there is an increase at bus 3, with the reason was the battery is charged to full in this period.

The power dispatch result is shown in Figure 42.

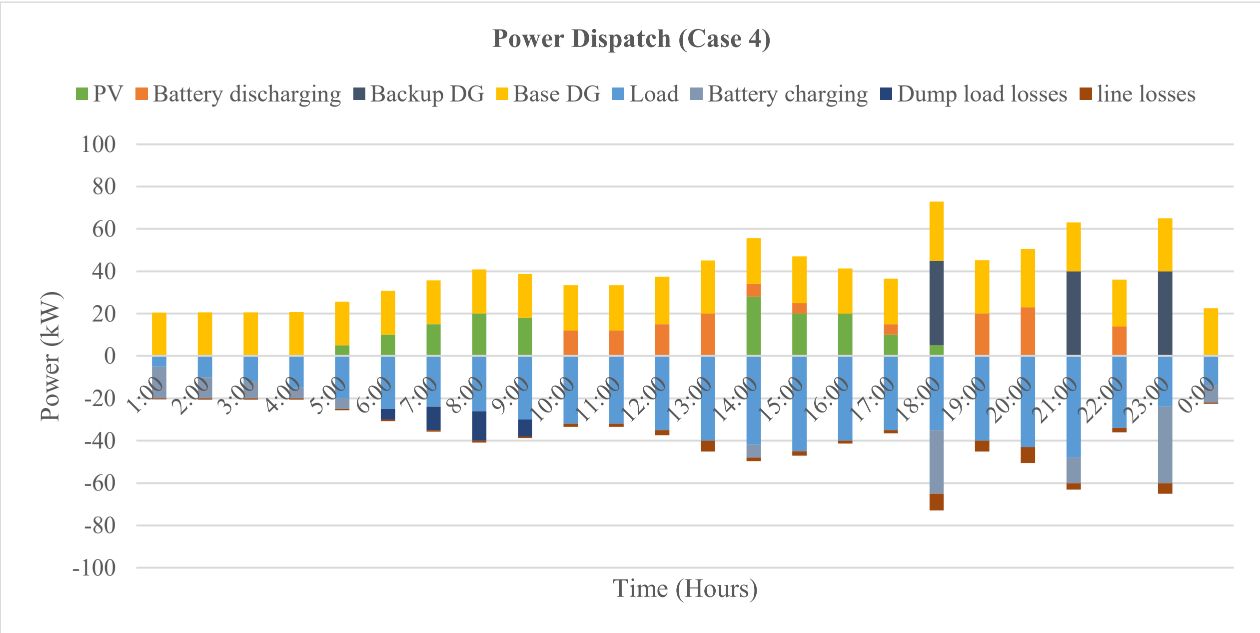

Figure 42 Power Dispatch (case 4)

The power generation and consumption percentage are shown in Figure 43, Figure 44 and Figure 45.

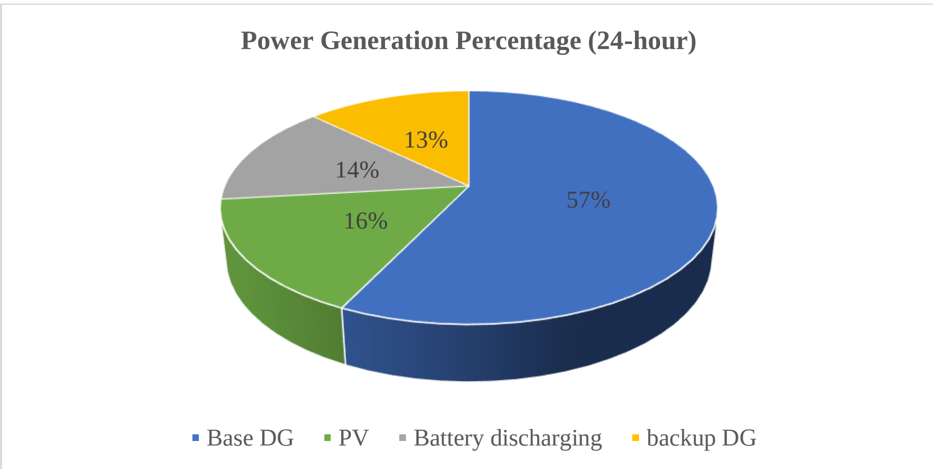

Figure 43 Power generation percentage (case 4)

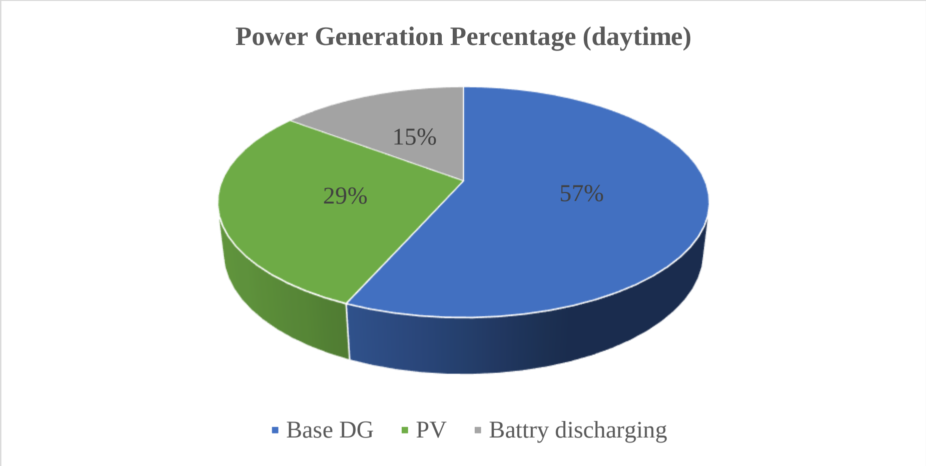

Figure 44 Power generation percentage at daytime (case 4)

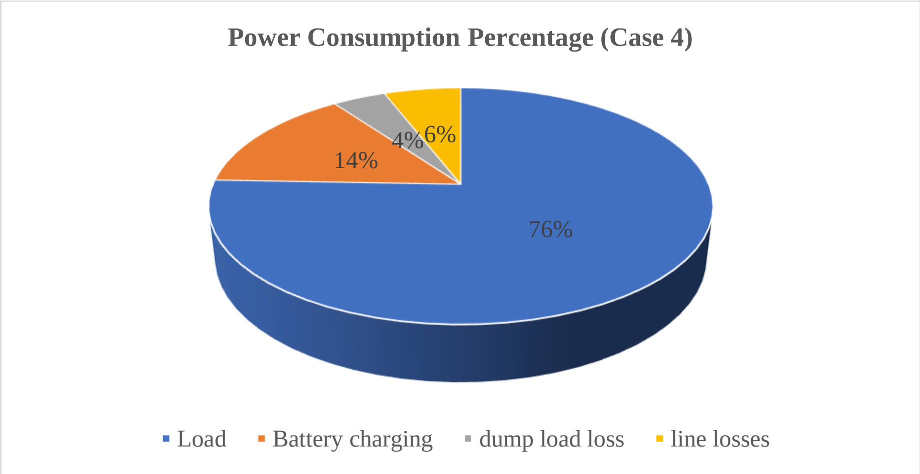

Figure 45 Power consumption percentage (case 4)

From the figures, the solar power accounts for only 16% in this case, and the battery and backup DG accounts for 14% and 13% respectively. The system mostly relies on base DG. In this case, the test system is operated under a cloudy weather condition with lower solar power generation. From the results of the case, the battery is a standby power source from 6:00 to 9:00. However, the solar power generation was zero during 10:00 to 13:00. During this period, the battery is discharged from 90% to 20% to maintain the power. The load demand increased continually from 18:00 to 21:00 and reached the second peak load at 21:00. During this period, the battery is at 20% state of charge, so it cannot produce power. The energy management system sent the signal to the backup DG for operation at 18:00, 21:00 and 23:00 respectively. The power generated by the backup DG is used to satisfy the load demand and charge the battery. By the end of the day, the battery is charged back to 90%.

4.5 Test Result Discussion

The proposed four case studies discussed verify the feasibility of the energy management system under different solar power generation conditions and different load profiles. As an islanded microgrid system design for a small residential area, the four case studies are based on a reasonable assumption of a typical residential area power consumption condition. From the bus voltage magnitude figures in all four cases (Figure 15, Figure 24, Figure 33 and Figure 41), the system proved to be well-operated.

Case 1 is for a high solar power generation and high load demand in the summer season. Case 2 is under low solar power generation but high load demand in the winter season. The irradiance and sunshine duration are lower than the summer. However, the electricity consumption during the winter season is high due to devices like heaters. Case 3 is to test the energy management system reaction to the sudden breakdown of some of the main power sources. Case 4 is for a cloudy weather condition. A comparison among the four cases will be discussed.

By comparing case 1 and case 2, the load demand is assumed to be the same at each time step. From the battery state of charge (Figure 21 and Figure 29) and power generation (Figure 16 and Figure 22), the battery in case 2 charges and discharges several times during daytime, accounting for 8%. On the other hand, the backup DG operated four times in case 2 which may increase the operational cost in winter. The battery charging/discharging ability is affected by ambient temperature. For winter time, if the islanded microgrid is built for a low-temperature area, the maintenance and protection of the battery are necessary.

By comparing case 1 and case 3, the backup DG operates once in case 3 at the second peak in the load time. In case 3, a sudden disconnection from the photovoltaic system happened at 11:00 and lasted for one hour. The proposed energy management system successfully dispatches the battery power to keep the power supply constant.

By comparing cases 3 and case 4, the islanded microgrid is operated in cloudy weather in case 4. The solar power is insufficient during daytime. The battery in the system is able to provide enough power supply for the first peak load from 14:00 to 15:00. And the backup DG is able to meet the load demand as well as charging the battery during its operation.

According to the power dispatch results from the four different cases, the EMS manages the power dispatch effectively by dissipating excess power generation to charge the battery in case of the sudden break down of the DG or photovoltaic system. It is important to have a self-protection ability during isolated mode operation. In case 1, the battery is a standby power source for most of the time during daytime. When the solar power generation is sufficient, both the backup DG and battery is used as standby power sources in case the base DG or photovoltaic breakdown. In case 3, when a sudden breakdown takes place, the standby power source operated once, avoiding a large failure in the system. On the other hand, in case 4, a cloudy day is considered resulting in low solar power generation. In order to protect the system from overloaded, the base DG and battery should have enough capacity. This EMS can be used to size the battery and base DG before the installation of a microgrid.

On the other hand, it is necessary to test the system performance for avoiding overvoltage or low-voltage problems. For this project, the load reactive power is used to adjust bus voltage magnitude. But in reality, the reactive power consumption is unchangeable. The bus voltage magnitude variation illustrates the load demand variation and power dispatch variation. The

EMS successfully managed the proposed islanded microgrid in a 24-hour time horizon. There is no overvoltage or low voltage problems in this system.

The battery is charged to the allowable maximum SOC when the solar power generation is sufficient in case 1 and case 4. However, under this condition, the excess power is dissipated to the dump load as this power is useless to the system. This may be decreased by increasing the battery capacity but the dump load consumption is unavoidable. In case 2, the solar power is relatively low, but the load demand is high, the power generated by the backup DG accounts for more compared with case one and case three. This may have a negative impact on the environment as well as increasing operating cost as the diesel generator has a start-up cost.

From the environmental friendly point of view, the proposed EMS operated effectively to dispatch solar power before the battery discharge power. If both solar power and battery power is not sufficient to compensate for the load demand, the EMS will dispatch the backup DG. In order to build an environmental friendly microgrid, the proposed EMS decreases the emission of carbon dioxide compared with the traditional mainly-DG electrical network. On the other hand, the proposed EMS consider renewable power sources before the traditional diesel generator. For the future microgrid installation, a larger capacity battery bank can be used for storing more power. But this depends on the solar irradiation and average temperature of the target area. The battery cycle life and charging/discharging ability is largely affected by ambient temperature[23]. Taking a typical lead-acid battery as an example, the battery capability of holding charge was found to decrease as the temperature goes down. When installing a battery bank in a microgrid, the ambient temperature should be taken into consideration. In low-temperature areas, the battery size should be smaller compared with high-temperature areas. On the other hand, in the low temperature condition, the battery life expectancy largely shortened. More attention should be paid to the protection and maintenance of the battery bank in low-temperature areas. From the battery bank state of charge figures of the four cases (Figure 21, Figure 29, Figure 33, and Figure 40), it can be seen that in case 1 and 3, the excess power is dissipated to the dump load during most of the daytime because the battery is fully charged. However, the battery capacity should be sized before the installation of the microgrid. In reality, for areas with higher irradiance and high load demand, a higher battery capacity can store more power, but this will cost more money.

According to the generation percentage figures in 24-hour period and daytime. Solar power accounts for the most power generation compared with other energy resources besides base DG. Before the installation of such an islanded microgrid, the prediction of solar power generation is necessary. The target area should also have enough space for a large solar power plant. The power generation capability, along with the amount of power consumption prediction should be carefully designed before any installation.

According to the four cases studies, the energy management system provides a reasonable power dispatch according to the given power generation and consumption during a certain time-horizon. For the installation of an islanded microgrid with a photovoltaic system as the main power source, the prediction of solar irradiance for a whole year-period and reasonable predictive load demand are necessary. For an area with sufficient sunshine in the summer period such as Perth, the scale of the solar power plant could be designed larger than areas with less solar irradiance if space is available. On the other hand, the size of the battery bank and base DG can affect the performance of the islanded microgrid. A battery with a larger capacity can decrease the dump load loss but may increase the charging time. However, the temperature in the area also plays an important role in the installation of a microgrid with the energy storage system. Since the battery is largely affected by ambient temperature. As for the base DG, from the four case studies results, the base DG should have a maximum power generating capacity of 55 kW. The base DG is a constant power source mainly for safety reason, but for an area with sufficient solar power generation, the scale of the base DG can be small to avoid producing dump load loss.

Chapter 5: Conclusion and Future Directions

This study presented an energy management system for the islanded microgrid based on the Gauss-Seidel load flow iteration process. The main objective of the energy management system is to dispatch power generated by various sources and balance power flow in the isolated microgrid. Furthermore, the management system dispatches renewable power sources before traditional diesel generators for the purpose of an environmental friendly power grid. Lastly, the energy management system power dispatch results are used for sizing the battery capacity and generating capacity of generators before the construction of the isolated microgrid. In order to verify the feasibility of the proposed energy management system, four case studies are analysed respectively.

From the case studies, all the objectives are achieved. Four cases are analysed in detail according to different seasons and different load demand. In case 1 and case 2. The decreasing of solar power generation increases the battery discharging power and the backup DG power generation. In case 3 and case 4, the EMS successfully keep the power balance in the islanded microgrid system by dispatching the power generated by base DG, battery and backup DG in cloudy weather or photovoltaic system suddenly breakdown. The EMS provides reasonable power dispatch in all four cases, proving that the EMS is operated well.

Firstly, the management system successfully dispatches intermittent power generated by a photovoltaic system and various power sources in the power grid. There is no overvoltage or overloaded problems. Secondly, the management system chooses solar power dispatching and battery discharging prior to diesel generators in the system. Based on different seasons and different weather condition, the power dispatch results indicate the optimal battery capacity and generating capacity of generators. Furthermore, the energy management system reacts to the sudden breakdown of the devices in the microgrid by dispatching standby power sources.

Energy management system is a necessary control and management strategy for the islanded microgrid. The management system optimises the power distribution within the system as well as making use of excess power generated by different power sources, which improves the power-quality.

The energy management system is necessary for an islanded microgrid. However, the system in this study has limitations. The prediction of power dispatch is affected by the accuracy of solar irradiation and load demand estimation. On the other hand, the climate in the area will affect the battery capacity and life cycle. If the islanded microgrid is for a low-temperature area, the extra protection and maintenance of the battery bank is necessary.

For future work, the system needs to be modelled in professional electrical simulation software for further tests. Additionally, more accurate solar irradiance and load demand estimation should be operated for more precise power dispatch results. The energy management system in this study is tested on the basis of the assumption, that an existing isolated microgrid model can be used for feasibility of the management system in the future. The function of decreasing the operating cost of the islanded microgrid is not included in this study. Future research direction, optimising the operational cost should be considered as well as exploring control strategies.

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